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COMPLEX SYSTEMS SIMULATIONS TO DEVELOP AGENCY AND CITIZENSHIP SKILLS THROUGH SCIENCE EDUCATION

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Abstract

In the era of big data, the progressively more widespread use of computational and data-intensive approaches is leading to changes in the ways of doing science and conducting research. The new methodologies and techniques are routine for researchers and professionals who make everyday use of big data analytics or simulations tools but are mainly unknown to ordinary people. Nevertheless, the impact of computational and data-intensive approaches has gone far beyond the scientific community, reaching the entire society. Indeed, the applications of machine learning and big data analytics, as well as the results and methods of computational simulations have reached people's life and behaviour and, even more importantly, are at the methodological core of studies on urgent issues like the climate change or the pandemic, on which policymakers and citizens have to make decisions. Hence, the educational community cannot ignore the ongoing transformation of all people's lives, behaviors, and culture. Within the research field of education to data science and computation, this dissertation addresses the issue of introducing in teaching-learning activities one of the methods of the on-going data science revolution: the computational simulations. Addressing the conceptual, methodological, and epistemological novelty of these objects, we will show how they embed, in a very specific, disciplinary-grounded way, the paradigm shift and cultural revolution of the data science age. We do that using lenses that come from the science of complexity, with its key-ideas that, originated from the physical modelling, can be applied to the analysis of a range of different phenomena. In the dissertation, we will guide the readers to recognize how dealing with simulations not only requires technical competences of coding, but a change of mindset and ways to think about the problems and the scientific method to address them.

The dissertation is articulated in three parts and seven chapters.

In the first part, we report three preliminary studies of exploratory and empirical nature, aimed at entering the topic of simulations of complex systems by trying to understand the difficulties that novices encounter when they are exposed to them and the ways they describe these tools.

In the second part, epistemological categories typical of complexity become the way to recognize in artificial neural networks and in the susceptible-infectious-recovered model two complex models that reflect in an "object" the cultural revolution brought by the complexity science.

In the third part we present two educational proposals targeted to university Physics and Mathematics students and to secondary school students on simulations of complex systems. Alongside the detailed description of the modules, which is grounded on the empirical results of the studies of Part 1 and the educational reconstruction of the contents of Part 2, we present the results of the implementations. The findings show that beyond the challenges they pose, if properly introduced, computational simulations can be the basis to foster in students the development of agency and citizenship skills through science education.

It is a privilege of few to have the opportunity, once in a life,
to dedicate to someone the material fruit of four years of thinking.

This is for my mum,
who shaped me in so many ways.

Table of contents

Preface

"May we live in interesting times"
(Probably a) Chinese traditional curse

"Change the instruments, and you will change the entire social theory that goes with them"
Bruno Latour in "Tarde's idea of quantification"

As a society, we are facing times in which so many transformations in such a short period have been taking place that it seems that, to make sense of them, we are often trying to conceptualize our times referring to them as an "era". The "era of pandemic", the "era of information technology", the "era of uncertainty", the "era of big data" are just few but very frequent examples of the tendency to speak about ourselves as the protagonists of something legendary and mythological, an "era" – implicitly assuming that an era can be described by living within its cultural, temporal, and spatial boundaries. If this could appear rhetorical, it illuminates the need to find consensus on words, names, and metaphors to express revolutions that, even if sometimes still lack a precise definition and characterization, are "happening around".

As part of the digital transformation which we are assisting to, it is manifest that something that in the last decade has been happening around is the increasing production, availability, and consequent interest on data. This "data revolution" (Kitchin, 2014) is impacting more and more the academia as well as professional and business environments. Indeed, all disciplines and fields of inquiry have now access to *big* data which are named in this way because huge in volume, high in velocity, diverse in variety, exhaustive in scope, fine-grained in resolution and uniquely indexical in identification, relational in nature, and flexible (Kitchin, 2013). In this sense, as we name the archaeological eras after the materials that were the basis of the technical progress in that period – the *stone* age, the *bronze* age, the *iron* age, or the mythological *golden* age – today data are so important that we could refer to our times as the *data* age. Data are everywhere and, most of all, are so precious that, for example, the European Commission developed a strategy aimed at ensuring "Europe's global competitiveness and data sovereignty" (European Commission, 2020, p. 1). Data are the new gold, data mean power.

The availability of data has been allowing scientists and professionals in all fields to perform analyses and extract knowledge from them with unprecedent effectiveness. New disciplines have been born on the ground of well-established ones: it is the case of the computational biology, computational physics, computational linguistics, computational sociology, computational mathematics, only to cite some of them. Although their names flank a traditional field with the adjective "computational", nowadays these disciplines are not only the result of a juxtaposition of some generically computational tools with the habitual objects of investigation: they are developing their own epistemologies, meaning that the computational dimension is determining a change in the ways these disciplines conceive the nature of knowledge they produce or address (boyd & Crawford, 2012). As a confirmation that the computational novelty is not (only) a matter of techniques, we are assisting to a progressive rise of new professional figures who monitor processes involving data to make them more transparent, fairer, and respondent to the needs of society (O'Neil, 2017; Veale & Binns, 2017). Therefore, we could argue that computational fields have been structuring themselves as scientific disciplines, with the establishment of new practices, methods, ways of producing and assessing knowledge, aims and values – categories that constitute a cognitive-epistemic system according to the Family Resemblance Approach to the Nature of Science (Irzik & Nola, 2011; Dagher & Erduran, 2016).

Due to the increasing data and data science's relevance and impact on society, the educational community we belong to could not ignore the ongoing transformation of our lives, behaviours, and culture. The directions of research in science education about data and data science have been various (Williamson, 2017) but can be summarized in two main branches: data science *for* education and education *to* data science. The former, with fields like Educational Data Mining and Learning Analytics (Romero & Ventura, 2010), sees in data science and in its methods a resource to understand how students learn or how teachers teach and, conversely, to improve their teaching or learning using tools like machine learning-based digital assistants. Our dissertation is positioned instead in the second branch, that of education to data science and computation.

In higher education, data science has been embedded in specific courses, from introductory ones which do not require any previous programming experience (Brunner & Kim, 2016) to specific educational and institutional experiences like the Ph.D. program in "Data Science and Computation" of the University of Bologna we have been taking part, the first of its genre in Italy. Effort has been dedicated also to the integration of the big data and computational dimension within established disciplinary domains, with the goal to give to university students competences required by society at large, a better understanding of the scientific method as well as deeper insights on the very same disciplinary aspects that are addressed from a computational perspective (Caballero & Hjorth-Jensen, 2018; Odden, Lockwood & Caballero, 2019).

However, the need for data and computational literacy does not invest only the field of higher education (Gould, 2021). Indeed, the data age touches all those who live within it, independently of the possible future choice of a university curriculum. Introducing data science's foundations and some of its elements in secondary education can be the way for students to do authentic interdisciplinary experiences that overcome the compartmentalization of knowledge in the schools and break the barriers between science, humanities, and society. Indeed, we believe this is one of the main messages that the revolution of data science and computation brings about: the possibilities of applying the same perspective, epistemology, and tools to disparate domains, beyond the traditional Manichean separations between quantitative and qualitative, natural and social, hard and soft sciences (Vespignani, 2019; Barabási, 2018).

To give our contribution to this debate, in our dissertation we focus on a specific method of the wide panorama of data science: the computational simulations. Addressing the conceptual, methodological, and epistemological novelty of these objects, we will show how they embed, in a very specific, disciplinary-grounded way, the paradigm shift and cultural revolution of the data science age. We do that using lenses that come from the science of complexity, with its key-ideas that, originated from the physical modelling, can be applied to the analysis of a range of different phenomena (Zanarini, 1996), as acknowledged also by the assignment of the 2021 Nobel Prize for Physics to Syukuro Manabe, Klaus Hasselmann, and Giorgio Parisi. In the dissertation, we will guide the readers to recognize how dealing with simulations not only requires technical competences of coding, but a change of mindset (Resnick & Wilensky, 1993) and ways to think about the problems and the scientific method to address them. However, we argue that beyond the challenges they pose, if properly introduced, computational simulations can be the basis to foster in students the development of agency and citizenship skills.

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2021, October 26th

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Dissertation's structure or The *story* told in this dissertation

The dissertation is articulated in three parts and seven chapters. Its structure is designed to tell the story of our journey as a Ph.D. student, from its early, preparatory stages to the final and more mature investigations, passing through the intermediate phases. Given the articulated structure of the dissertation, to guide the readers through it, we provide an overview of the work, of the three parts and the seven chapters. The aim of this storytelling is to make the readers comfortable in "cherry-picking" in advance the parts or chapters they are more interested in, but also to orient them grasping the different roles that the three parts have in constructing the *thesis* of this dissertation.

In Part 1, we address the *pars destruens* of the thesis. We report three preliminary studies that we conducted during the first two years of the Ph.D. program. They have an exploratory and empirical nature since they were designed to enter the topic of simulations of complex systems by trying to understand the difficulties that novices encounter when they are exposed to them and the ways they describe them. In this sense we have named this part the *pars destruens* of the dissertation because, through the preliminary findings obtained, it allowed to point out the critical points to address in the following chapters. In the first part we have three chapters, each of them dedicated to one of the preparatory studies.
In Chapter 1, we present a study conducted with adult citizens, novices with respect to complex systems and simulations, who were involved in a citizenship education experience. We investigated if, how and why the development of hard scientific skills grounded in the discipline of complex systems (suitably simplified and adapted) might foster the development of citizenship skills that can impact on people's approaches to facing complex societal problems and making decision on these issues. Among the variety of tools used, the features of complex systems were introduced through some computational agent-based simulations who were proposed to participants to visualize and "see in action" some typical properties of complexity, e.g. emergent behaviours and circular causality. An unexpected finding of this study was that these tools, that we, as designers, considered particularly well-positioned to develop the scientific basis to develop citizenship skills (allowing, for example, to perform some experiments on different working conditions), ended up triggering some resistances. The game-like interface of the simulations challenged the image that participants had of a "science for specialists" and they were not appreciated for their scientific authenticity of tools that embed a mathematical model but only as mere games.
In Chapter 2, a study with secondary school students is presented about the explanations formulated by the participants about emergent phenomena displayed by computational simulations. The students, novices about complex systems and simulations, were interviewed in pairs and exposed to four different simulations: one about the Schelling's model for racial segregation, one about the Lotka-Volterra predation dynamics, one about the ideal gases and a video about the results of a simulation on climate change. After a review on the conceptions of explanation within science education (from explication to mechanistic, covering-law, teleological

and intention-based explanations), we investigated what factors influenced students' attitudes toward the selected simulations and their level of trust. The main findings related to the fact that the attitudes toward simulations were connected to students' epistemological beliefs who were influenced by the kind of instructions that the students were exposed so far. In particular, the students who had not addressed during their curricula the issue of scientific modelling from an epistemological point of view struggled in trusting the simulations as scientific models with their own "cuts" with respect to the reality. This suggested us the importance of an appropriate introduction and contextualization of simulations to underline the modelling purposes of simulations, their assumptions, and limits of validity. A further implication of this study that strongly impacted the structure and direction of this dissertation regarded the choice of simulations proposed to the students. For the next studies, we clearly distinguished between simulations created for educational purposes and simulations developed for scientific investigations. Moreover, we always made available to students the codes of the simulations proposed (using for example the NetLogo language) which they were guided to explore in order to see "what is behind" the surface of the interface.
After having presented two studies with adult citizens and secondary school students in the first two chapters, Chapter 3 provides insights into the understanding about scientific simulations of university Physics and Mathematics students enrolled in a course of Physics Education. Before an intervention on complex systems, a questionnaire was submitted to the participants in order to collect their ideas about the topic. The chapter contains a review of the literature in epistemology of science, discussing definitions of simulations, their relationship with experiments and models and the main types of simulations in the sciences. The qualitative process of data analysis allowed to point out different ways in which simulations are conceptualized by the students, in terms of scope for which simulations are used, their relationship with experiments and models, and the examples of simulations they refer to. We understood that the main reference for physicists about simulation were the issue Monte Carlo simulations – whose status of simulations is often questioned by philosophers of science. Moreover, the analysis showed some great absentees in the students' ideas about simulations that are particularly important when it comes to agent-based simulations: the issue of their epistemic opacity and their explanatory power. These findings were the basis for the design of teaching sequences about computational simulations targeted to prospective Physics and Mathematics teachers.

Part 2 is the core part of the dissertation, its epistemological heart. Here, we report the studies conducted during the second and third year of the Ph.D. program to investigate the epistemological revolution of complexity through machine learning and computational simulations. Vice versa, epistemological categories typical of complexity become in this second part of the dissertation the way to recognize in artificial neural networks and in the susceptible-infectious-recovered model two complex models that reflect in an "object" the cultural revolution brought by the complexity science. The neural networks and the SIR model are the case studies addressed in the two chapters of part 2. Even if the contents of these chapters were at the basis of the design of several lectures targeted to secondary school students, pre-service and in-service teachers, in these chapters we do not report nor analyse the data from the implementations. Indeed, their original character lies in the educational reconstruction of the disciplinary contents from conceptual, epistemological, and societal perspectives. We refer to this second part as the *pars construens* of the dissertation since it sets the basis, on a multiplicity of levels, for the design and implementation of the teaching proposals that are presented in the third part.

Chapter 4 aims at identifying which discourses can be introduced to upper secondary-school students to make them aware of the epistemological and cultural revolution introduced by machine learning. As a case study, we describe an educational activity about the topic of artificial neural networks, designed and carried out within a teaching-learning module on artificial intelligence. The hypothesis that guides the analysis of the activity is that machine learning revolution shares some epistemological traits with that introduced by the science of complexity. Indeed, both imply and require a shift from classical determinism to probability, and challenge the classical definition of explanation of phenomena, because of the epistemic non-reductionism. Basing on this assumption, the activity discusses the parallelism between neural networks and complex systems, referring to a specific system that the students had encountered since the beginning of the module: the birds' flock. The main similarities identified were the emergence of higher-order properties from local rules of individual agents, the input-output and local-global circularity, and the presence of non-linearities. We argue how the interpretation of neural networks as complex systems allows to illuminate the epistemological change introduced by machine learning – specifically by the connectionist paradigm – with respect to other approaches to artificial intelligence: the emergence of knowledge from data and the sub-symbolism of the approach.

If in the previous chapter the revolution of complexity is exploited in relationship with the machine learning approaches, in Chapter 5 the analysis stems on the comparison between equation-based and agent-based approaches to computational simulations. Through the analysis of the case study of the Susceptible-Infectious-Recovered model and the comparison of equation- and agent-based approaches to its simulation, we discussed how simulations can be a very interesting case to show in teaching the change in the scientific paradigm from the Newtonian and deterministic view of science to the contemporary one based on probability, discretization, and emergence. The fine-grained zoom on the mathematical, physical, and computational disciplinary details embedded in simulations allowed to point out the epistemological aspects that characterize complex systems and that are implemented in the mathematical and computational SIR models. The results of the epistemological analysis are then discussed in the light of the OECD Learning Compass 2030 framework and the recent findings of literature in future-oriented science education. In particular, we will highlight the contribution of the present work to the operationalization of transformative competencies, of the Anticipation-Action-Reflection cycle and of future-scaffolding skills within a specific scientific topic.

Part 3 is dedicated to the presentation of two educational proposals targeted to university Physics and Mathematics students and to secondary school students on simulations of complex systems, whose implementations took place during the third and fourth year of the Ph.D. program. Alongside the detailed description of the modules, which is grounded on the empirical results of the studies of Part 1 and the educational reconstruction of the contents of Part 2, we present the results of the implementations. The two chapters result particularly dense also because we dedicated much effort, time, and research investment on the analyses they relate to – respectively about the role of simulations to support decision-making processes and to foster the development of future-scaffolding skills.

Chapter 6 reports a study in which university Physics and Mathematics students were exposed to a 7-hours teaching-learning module on computational simulations in which the core activity was a role play based on an agent-based simulation about the processes of recruiting to terrorism. The chapter and this peculiar choice of problem context stem on Part 1 of the dissertation where the game-like character of simulations hindered novices to recognize that these tools can actually suggest concrete actions and support reliable decision-making processes. For the study presented in this chapter, we chose a particular agent-based simulation that was developed by physicist within a Horizon2020 project to support policymakers in decision-making on counter-terrorism policies. We found this problem particularly well-positioned to respond to the criticisms raised by the previous studies because it was an intrinsically complex problem that could inspire an authentic decision-making process. Indeed, the formation of terrorist networks can be modelled on the basis of local mechanisms of interaction inspired to the theory of opinion dynamics. Moreover, the use of a complex simulation made us reflect on the different kinds of scientific information that a simulation and the related model vehicle. This un-packing of the knowledge elements behind a simulation led to the design of a role-play activity proposed to university Physics and Mathematics students on the issue of terrorist groups' formation. The data collected during the role-play activity were analysed to identify which forms of reasoning the students put into play when dealing with a complex societal problem though a simulation, and which forms of reasoning are triggered by the various elements of the simulations, e.g. data, graphs, scenarios, parameters, and model.

In Chapter 7 we present the design, implementation, and analysis of an 18-hours module on simulations of complex systems targeted to upper secondary school students. This module was situated in the context of the Italian national program PLS (*Progetto Lauree Scientifiche*) that aims at orienting high school students to the choice of a scientific university curriculum. The module had not as its only goal that of leading students to enrich their conceptual knowledge about the topic of simulations but also aimed at making students reflect on the wide potential of computational simulations to provide knowledge on societal issues, to think about interdisciplinarity and to enrich their imagination and ways of thinking about the future. On the basis of the design principles, in the chapter the module and all its original activities will be described in detail. During the first implementation of the module with 35 participants, several data were collected through questionnaires, focus groups, collective discussions, and individual interviews. The richness and multidimensionality of data led us to identify different *foci* of analysis. The main analysis aims at investigating the module's potential in fostering the development and the put into action of future-scaffolding skills as abilities to navigate the uncertainty of the future through a rational scaffolding. Moreover, in the light of the empirical results of the part study, we present an operationalization of these skills as competences that can be grounded in the conceptual and epistemological aspects embedded in agent-based simulations and in the design principles of the module itself. Beyond the core analysis on future-scaffolding skills, we report three additional part studies that analyse different aspects of the module's implementation. In the first part study, we investigate the module's potential in making students use given models and simulations to address a range of diverse real-world phenomena. In the second part study, we investigate one of the main features of the scenarios obtained by the students in the future-oriented activity of the module which is the idea of equilibrium. Finally, the third part study is dedicated to the analysis of the ways in which the students used the future-oriented activity as a "free thinking space" that allowed them to discuss about the problems of the school in the present and their idea of desirable school for the future.

Visual representation of the dissertation's structure

In this storytelling, we tried to highlight how the various parts and chapters contributed to the development of the "thesis" of the dissertation. In Figure 1 we present a visual representation of the structure. We think that for some readers it can be useful, like a compass, to navigate also graphically the global scaffolding of the dissertation, the relationship among its parts, and the argumentation developed. All the studies conducted during the four years of the Ph.D. program contributed to the following analyses, in some cases to confirm some intuitions and in other cases to unveil other problematics or to identify needs that until that moment had not been taken into account. Figure 1 is structured in three blocks that correspond to the three parts of the dissertation.

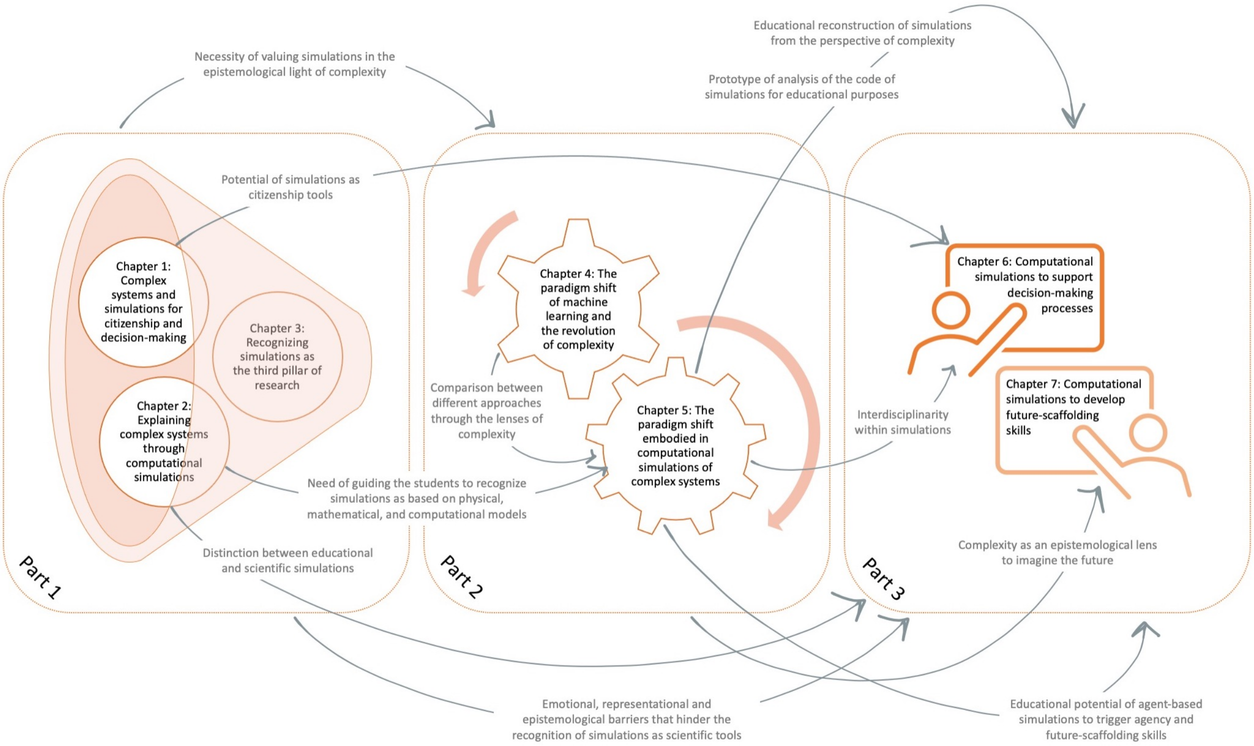

Figure 1. Visual representation of the dissertation's structure.

Part 1, on the left, is the preparatory section that contains three preliminary studies. Its role is to delimit the field of inquiry – the graphical element we chose is the section of a cone – from the wide literature on the topic of simulations to our focus of investigation and research problem.

Part 2 is positioned in the middle and its graphical elements are two gearwheels. They represent the concreteness of this part, in which disciplinary details of artificial neural networks and computational simulations were unpacked and analysed. At the same time, we want to communicate the idea that the core of the dissertation is not the analysis of the technical aspects *per se,* but these wheels are put into gear and coordinated by the analysis in the perspective of complexity that allows to value the paradigm shifts of machine learning and computational simulations.

Part 3, on the right, is the last section with the two chapters that include the design principles, description, implementation, and data analysis of two modules on computational simulations. The graphical element of the whiteboard is related to the fact that these modules were implemented by us with groups of university Physics and Mathematics students and high school students.

The arrows are the most important part of the representation. Some of them goes from specific studies to other specific studies, others go from a chapter to a whole part, and still others connect big blocks to each other. They represent findings of studies, intuitions reached confronting some results, changes of direction. In few words, the arrows tell the story of our research: a *non-linear* story but still with *emergent* structure and sense.

Acknowledgments

After four hundred pages of dissertation, it has been three hours that I am in front of this white page, trying to figure out how to explain in a meaningful way the *complexity* of what my thoughts are like right now. It is like being at an amusement park when you end your ride on the rollercoaster, high on adrenaline, and find out that an automatic service has been taking pictures of you screaming, smiling, being terrified, or doing nothing. It is pretty much like that, in this exact moment, when I am approaching the end of my personal Ph.D. rollercoaster. I am recalling pictures of extreme joy and satisfaction, others of disappointment and anger, and (many) others of boredom and frustration for results that seemed not to come up. Being a doctoral student is not an ordinary job. Not having "working hours" simply means that job potentially expands, like a gas, to occupy all the available space. Hence, the demarcation between life and work has not always been clear-cut. Certain steps in the investigation profoundly impacted my personal life which, in turn, affected research directions, interests, and sensitivities.

The first acknowledgment goes to the reviewers of this dissertation, Sharona Levy and Danny Caballero, who dedicated their time to a careful reading of my work. Your comments and insights were truly inspirational and allowed me to strengthen the argumentation of the thesis, reaching the shape in which it is now.

At the end of this journey, I want to take this opportunity also to thank the people who, along the road, have been travel companions, friends, pioneers, supporters, mentors, and cornerstones.

To my advisor Olivia Levrini, my guide and mentor from the very beginning of this research path. You encouraged me along the road, setting the pace, the times, the modalities when needed, but you also left me free to explore my inclinations. In the research group, you created a space of circulation of ideas and *beautiful thoughts*, and a fingerprint of the ways of conducting research. Your passion, intellectual work, and intuitions profoundly shaped this dissertation.

To my colleagues of the research group in STEM education of the University of Bologna, and in particular to the Nerd+ division. To Laura Branchetti, Paola Fantini, Giulia Tasquier, and Sara Satanassi. Discussing with you made progressively emerge the core ideas of this thesis and of my research. I like to think at our group as a choir, where a pitched sound is the result of the voices of the individual singers. And it does not matter if the pitched sound emerges in a paper published on an international journal, in a symposium at a conference, or in passionate talks at Rimini's beach, *quando il cielo smucchia*. I have learnt so much from each of you and I hope that in these pages you will find something yours. A special thanks to Sara, for being on the same doctoral boat in the last two years and a half, for the mutual support we are constantly giving one another.

Since I started working in the Bologna research group, it has been incredible to see it enlarging and welcoming new people. It did not only grow in size, but became truly interdisciplinary, as a place of contamination allowing its members to cross disciplinary boundaries thanks to the presence of experts in different fields. To Giovanni Ravaioli who accompanied me during the first years of my research journey. To Martina Caramaschi, Francesco De Zuani, Lorenzo Miani, and Andrea Zanellati: I hope that the Ph.D. will be for you an experience of intellectual, personal, and professional growth as it has been for me. To the computer science division, Michael Lodi and Marco Sbaraglia. To our linguist, Veronica Bagaglini. A special thanks to Gianni Zanarini, for inspiring me the charm of complexity and the poetry of physics.

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With I SEE, I began my work for the master dissertation and started to experience the power of the collaboration among different research traditions, approaches, and methods. Thanks to the teachers of the Liceo Einstein of Rimini (Michela Clementi and Fabio Filippi), the colleagues of the University of Helsinki (Antti Laherto and Elina Palmgren) and to Caitlin Wilson. Together, designing modules and analyzing data, we questioned our same ways of thinking at the future.
The dream for a desirable future of STEM education is what inspired the FEDORA project. I am honored and grateful to be part of such an amazing team, working side to side with researchers from the University of Oxford, Helsinki, and Kaunas, and with the professionals of Teach the Future and formicablu.
With IDENTITIES, I realized how challenging and amazing is working on interdisciplinarity keeping a disciplinary identity. To the colleagues of the University of Crete, Montpellier, and Parma. A special thanks and a big hug to the research team of the University of Barcelona. To Berta Barquero. Thanks for welcoming me in your group and for the constant support. To Mariana Bosch, Joaquim Giménez, Carolina Pipitone, Oscar Romero, Gemma Sala-Sebastià. Thanks for the work we have done together on the coronavirus module, from the co-design experience to the implementation and data analysis. A special thanks to Maria Rosa Aguada Bertea. Few words would never be enough to say how much your encouragement and *cariño* have been important to me. *Salut* to our friendship, to the past and future days of data analysis drinking mate, and to the nights of chats drinking vermouth.

This dissertation was only possible also thanks to those who, without asking to know anything of it, helped me, in these challenging years, *a non disurnirmi*. To stay alive, to remain focused, to keep fighting, to rest.

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To my family. To Agnese and Liliana, my grandmothers. To Italo and Giancarlo, my grandfathers. To Elena, my aunt. To my parents, Euro and Silvia, and my brothers, Edoardo and Alessandro. You are the cornerstone of my life. Words cannot express how much I love you.

To Eugenio. You saved my life and make it better every day. Thanks for being *the house where my heart lives*.

Concordia sulla Secchia
2022, February 14th

Part 1

In Part 1, we address the *pars destruens* of the dissertation. We report three preliminary studies that we conducted during the first two years of the Ph.D. program. They have an exploratory and empirical nature since they were designed to enter the topic of simulations of complex systems by trying to understand the difficulties that novices encounter when they are exposed to them and the ways they describe them. In this sense we refer to this part as the *pars destruens* of the dissertation: through the preliminary findings obtained, it allowed to point out the critical points to address in the following chapters.

Chapter 1 – Complex systems and simulations for citizenship and decision-making: a study with adult citizens in a civic education context
Chapter 2 – Explaining complex systems through computational simulations: analysis of interviews with high school students
Chapter 3 – Recognizing simulations as the third pillar of research: analysis of questionnaires from university Physics and Mathematics students within a course of Physics Education

Chapter 1 - Complex systems and simulations for citizenship and decision-making[1]

The issue of scientific citizenship in the context of STEM education has been under debate for over two decades. We present a preliminary study which aims to investigate if, how and why the development of hard scientific skills grounded in the discipline of complex systems (suitably simplified and adapted) may foster the development of citizenship skills that can impact on people's approaches to facing problems and making decisions. We carried out a pilot study with a group of 34 volunteer adult citizens. The data analysis showed that: i) in the beginning, only a few participants were comfortable dealing with scientific and epistemological concepts related to complex systems, favouring instead a "common sense" approach towards decision-making; ii) in some successful cases, there was an alignment between scientific competences and decision-making strategies, suggesting that it is possible to design activities based on authentic scientific concepts in order to develop citizenship skills. Our approach is meant to make an original contribution to the literature about scientific citizenship, since:

- it presents original activities on the science of complex systems and shows how the educational reconstruction of the mathematical models, and the scientific disciplinary contents can foster the development of citizenship skills and stimulate rational attitudes towards collective decision-making;
- it is sustainable for citizens (in terms of time spent on tasks at home and in collective meetings, preliminary skills and knowledge required) and encourages non-experts to deal with activities based on mathematical modelling and scientific concepts;
- it allows the spontaneous emergence of citizens' attitudes, and informs activities designed to involve adults in analysing complex problems (as a group) and making collective decisions.

[1] The contents of this chapter are the object of a paper entitled "Science of Complex Systems and Citizenship Skills: A Pilot Study with Adult Citizens" (Barelli, Branchetti, Tasquier, Albertazzi & Levrini, 2018) which is based in turn on the homonymous extended abstract accepted for a poster presentation at the ESERA 2017 Conference (Barelli, Albertazzi, Tasquier, Branchetti & Levrini, 2017). The work is a follow-up of our work for the master thesis (Barelli, 2017).

1. Research Framework

1.1 STEM education for citizenship

For over two decades, within the field of STEM (Science, Technology, Engineering and Mathematics) education, a crucial importance has been attributed to the issue of citizenship education in general and to scientific citizenship in particular. The Eurydice report (Eurydice, 2012) affirms that, in order to increase engagement and participation, "people must be equipped with the right knowledge, skills and attitudes" (p. 3), including social and civic competences; these are among the eight key competences identified in the recommendation of the European Parliament and of the Council (EPC, 2006) as essential for citizens living in a "knowledge society". In one of the first reports on this topic, *Beyond 2000: Science education for the future* (Millar & Osborne, 1998), some experts in the field of Science Education stressed the need for a dialogue between science and society "to sustain a healthy and vibrant democracy" (p. 4), through a renovation of STEM curricula. The main goal was to build public awareness among citizens who, whilst appreciating the value of science and its contribution to our culture, can critically engage in issues and debates that involve scientific knowledge. Since 1998, the EU has pursued similar goals by proposing research programs like *Science in Society* (2007-2013) and the most recent *Science with and for Society* within *Horizon 2020.* The history of programs about scientific citizenship shows a progressive integration between science and society, culminating in an approach in which all societal actors, both shareholders and stakeholders (Greco, 2014), are encouraged to work together throughout the entire research and innovation process. This kind of public participation in scientific research is the real essence of citizen science which also takes advantage of living laboratories (Mitchell, Larson & Pentland, 2010), tangible environments that embody this type of choral conception of scientific research and practice. The necessity of providing "the space for open, inclusive and informed discussions on the scientific research and technology decisions that will impact citizens' lives" (p. 5) is also underlined in the EU report which was presented and discussed at the 2015 ESERA conference in Helsinki (EC, 2015).

In order to make the EU recommendations operative, it is necessary to explore new approaches and design innovative ways to develop citizenship skills on the basis of scientific knowledge. The most common approach is summarized by Osborne (2010) who has stressed the need for "less emphasis on the facts of science and a broader knowledge of how science works" (p. 67). Our aims were slightly different, since we used scientific concepts as bases to scaffold citizenship skills. Indeed, we investigated if, how and why the acquisition by citizens of hard-scientific skills (skills based on authentic scientific concepts, problems, and methods) could result in the development of citizenship skills (skills able to impact on people's approaches to problems, such as the skills necessary for making informed decisions about societal issues).

The scientific discipline that we retained appropriate in this study in order to acquire a good basis for the development of such competencies is the science of complex systems. In the following paragraph, the reasons for this choice are discussed and we argue specifically as to why it can provide a contribution to the development of citizenship skills; in particular, we clarify what we mean, in our context, for hard-scientific skills and citizenship ones.

1.2. Science of complex systems as a heritage to develop citizenship skills

Within the scientific community, complex systems are usually defined in terms of their features and behaviour they display: in such systems, numerous individual elements or agents, often relatively simple, interact with each other and the resulting systems frequently display features that the classical ones do not have, such as non-linearity, high sensitivity to initial conditions, feedback loops, self-organization and emergent properties (see, for example, the Wikipedia article "Complex system"). The science of complex system is an intrinsically interdisciplinary field since the same general approach regarding the role of the mathematical modelling informs all the application contexts. Examples of complex systems can be found in many disciplinary fields: in scientific fields, such as the climate in climatology, living organisms and cells in biology, the human brain in neuroscience, and ecosystems in ecology but also, concerning economics and sociology, in social and economic organizations like cities (Omicini & Contucci, 2013). The consequence of considering a specific system as complex is that it can be approached (from both quantitative and qualitative perspectives) with an appropriate attitude and a suitable conceptual, technical, and epistemological framework.

Together with its set of concepts, which are generally absent in classical physics, the science of complex systems has developed specific methods of analysis, including computational simulations. Going beyond the traditional laboratory experiments and theories, simulation can be considered the third important tool of science (Parisi, 2001): when a simulation runs on the computer, it gives rise to empirical predictions that derive from the theoretical mathematical model of the phenomenon under exam, and it works as a virtual laboratory in which, just as in the real laboratory, the researcher monitors the phenomena under controlled conditions, manipulates the conditions themselves and discovers the consequences of such manipulations.

Research in the field of science education has been investigating students' difficulties in learning about the basic concepts and methods of the science of complex systems, showing to what extent they can be challenging to learn (Jacobson & Wilensky, 2006). Indeed, many concepts may be counterintuitive or in conflict with common beliefs (Casti, 1994; Wilensky & Resnick, 1999): for example, the idea that small causes correspond to small effects while large effects result only from large causes is common; moreover, it has been proved that people also tend to use deterministic causality and "top down" approaches to describe systems in which self-organization, with its decentralized processes, is displayed (Resnick & Wilensky, 1993; Feltovich, Spiro & Coulson, 1989). These findings, documented by the research literature, anticipated us the challenges we were expected to face working with adult citizens with different backgrounds; indeed, we imagined that they could approach problems using, more or less explicitly, their common beliefs, since they could feel unease with counterintuitive ideas.

Because of its new concepts and methods, the science of complex systems has laid the foundations of a new epistemology (Morin, 1986) characterized mainly by: the concept of uncertainty, a new approach to causality and a focus on the role of the single agent within the system. This new epistemology is very different from that which was embedded in the linear determinism of classical science (e.g. Newtonian physics) and which is often implicit in science teaching at school and in most citizens' conceptions of physics. In order to understand the phenomena under examination, such an epistemology requires a change in learners' perspective. The learners' difficulties about science of complex systems has been interpreted also in terms of a widening gap between science and citizenship (Jacobson & Wilensky, 2006) or, better, between, on one hand, the scientific communities and, on the other, policymakers and citizens. Indeed, challenging social and global problems of the 21st century often require scientific competences coming from this new scientific perspective of complexity. Many problems, whether on a local or global scale, from decisions in municipal councils about urban planning to global debates about climate change, often require an awareness that actions can have multiple causes and consequences that constitute non-linear patterns of interaction, since positive and negative feedback loops exist and contribute respectively to the divergence or equilibrium of the system (Omicini & Contucci, 2013). Nowadays, also because of some weaknesses in STEM education, citizens are not equipped with the knowledge and skills usually needed to face these complex problems and challenges. For these reasons, we argue that the science of complex systems is suited to addressing the citizenship issue, as it can be considered a heritage of concepts and methods capable of fostering specific skills and, then, of informing citizens' approaches to facing problems and decisions.

The goal of our work is to outline an approach that can explicitly support the teaching of the basic concepts of the science of complex systems in informal contexts of adult citizen education. The approach results in the design of activities aimed both to introduce basic concepts of the science of complex systems and to turn "hard-scientific skills" into "citizenship skills". By "hard-scientific skills" we mean skills that typically belong to science, like the ability to give up linear causality to embrace circular patterns of complex relationships between causes and effects, recognizing feedback loops. By "citizenship skills" we mean skills needed to address typical citizenship issues, like the ability to make decisions, to recognize the various stakeholders involved in a civic problem and so on. As we will show, in our activities hard-scientific skills are exploited to reveal their potential in contexts that go beyond science and, in this sense, they are expected to become citizenship skills.

In the next sections, we present the activities that we designed for a pilot study in which adult citizens were involved.

2. The pilot study: context, design, and data collection

The pilot study was carried out in collaboration with Luca Albertazzi, one of the co-authors of this paper, who is the Mayor of Dozza, a little town close to Bologna (Italy). The group of people involved in the qualitative study consisted of 34 volunteer adults recruited by the mayor to represent a heterogeneous sample of the local citizens (Albertazzi, 2017): they differed in age, gender, job, scientific education, and type of engagement in the local administration. The graphs in Figures 1-3 give a more concrete idea about the composition of the sample, showing some correlations between the characteristics taken into account when recruiting the sample group. The sample composition is particularly relevant as the whole planning process had to consider evident differences between the participants, particularly regarding their professional roles and level of scientific education.

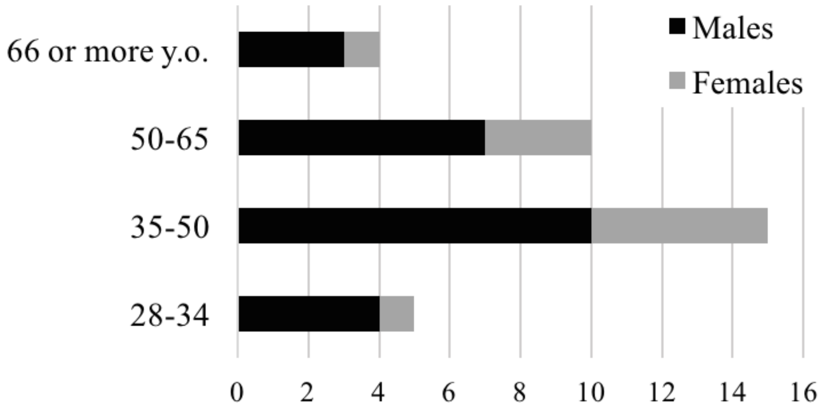

Figure 1. Age distribution of the sample (Total number of citizens: 34; number of males: 24; number of females: 10).

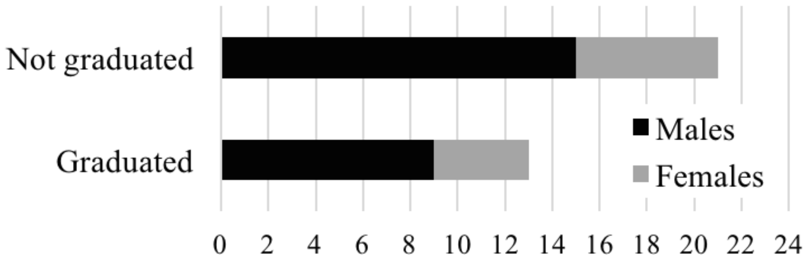

Figure 2. Differences in education between males and females in the sample (Total number of citizens: 34; number of males: 24; number of females: 10).

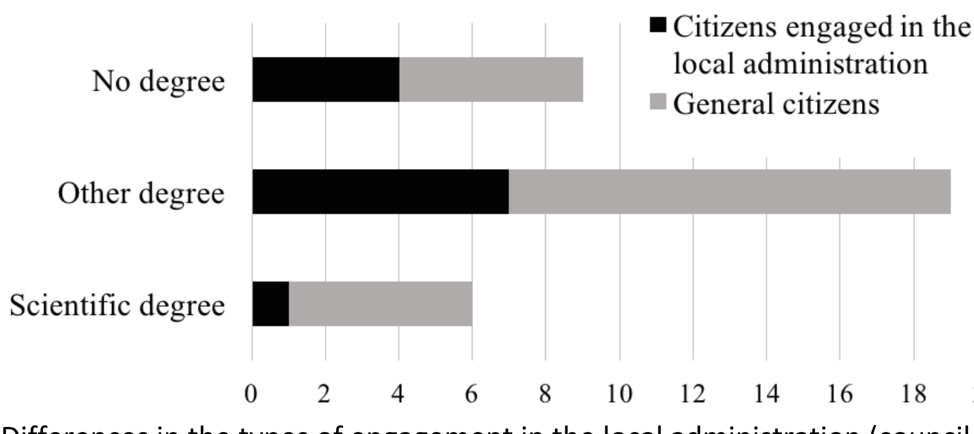

Figure 3. Differences in the types of engagement in the local administration (council members or assessors) according to the participants' education (Total number of citizens: 34; number of citizens engaged in the local administration: 12; general citizens: 22)

Across all the phases of our teaching/learning experiment, we collected data about citizens' progressive development in order to answer two research questions that we present in the Data Analysis section. The study was articulated in three phases and a set of original activities was designed for each stage by our research group in STEM Education of the University of Bologna: a summary diagram is provided in Figure 4.

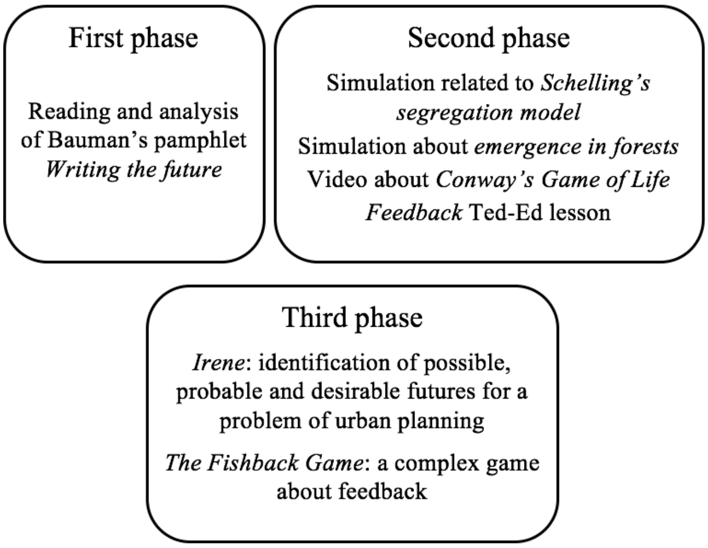

Figure 4. Outline of the activities across the three phases of the experimentation.

2.1. First phase

The first phase has been designed with the aim to introduce the citizens to the conceptual apparatus of the science of complex systems. In this context, we also planned to investigate whether and how the group of citizens held scientific and epistemological knowledge about science in general and science of complex systems in particular. For these purposes, the participants were asked to read and analyse a pamphlet by Zygmunt Bauman (2016) in which the Polish sociologist used terms derived from the science of complexity (such as uncertainty, order, turbulence, system, probability, predictability) in order to interpret recent social transformations like migrations, assimilation of strangers, and gated communities characterized by the dualism between mixophilia (the attitude of attraction and tolerance toward strangers) and mixophobia (the tendency to avoid relationships with people of other cultures in the effort to safeguard personal goods). Bauman's argumentation begins by presenting the concept of determinism *à la Laplace*, in which the future is certain since, as a matter of principle, it is perfectly predictable by a supreme intelligence who could precisely measure the state of all the components even of a huge and complicated system. Secondly, the *world of becomingness* is presented with its characteristic concepts, including uncertainty, probability, instability, irreversibility, and future. Continuing his argumentation, Bauman introduces the term *complex world* to refer to the presence of apparently contradictory processes made of both order and chaos and characterized, within a new view of causality, by a strong dependence on initial condition; in this kind of world, the renunciation of a deterministic certainty is associated with the relevance of every action of every single member of the system, who consequently carries a high degree of responsibility since he/she can really make a difference. The pamphlet ends with the sociological analysis of some noticeable on-going social transformations, pointing out the role of

single choices of individuals within a world that cannot be considered anything other than authentically complex.
This text is substantially the transcript of a public lecture addressed to citizens within the context of the 2014 edition of *Futura Festival* in Civitanova Marche (Macerata, Italy). Considering the general public nature of that audience, the author wished his language to be straightforward and comprehensible to a citizen without any presupposition about mathematical, scientific or sociological knowledge. This feature of the text convinced us to use it for the first phase of the educational intervention, since our audience was quite varied in terms of scientific education. In practice, we prepared a questionnaire (Q_A) with two sections and the participants were required to read the pamphlet and to answer, either by writing or by oral interviews, some questions about the content of the text. In the first section, there were 11 guided open questions aimed at focusing the debate on salient points of Bauman's argumentation, with specific attention to the scientific terms used by the author (e.g. *How would you explain, in your own words, the fundamental meaning of Laplace's claim? Why does the author write that this is a "seductive perspective" and which less "seductive" consequences does (or did) it have? What characterizes the "world of becomingness"? In your opinion, does the "world of becomingness" have positive or seductive aspects? If so, which ones? If not, why? What characterizes the "complex world"? In your opinion, does a "complex world" have positive or attractive aspects? If so, which ones? If not, why?*). Consistently with the double goal of the study, the questions were supposed not only to direct the readers to reflect on the main concepts of the text as a sort of guide to reading (educational goal), but also to encourage answers that could show the citizens' level of scientific and epistemological knowledge (research goal). These answers allowed us to elaborate a description and categorization of the initial state of the group in terms of attitude towards such scientific concepts and societal challenges.
The second part of Q_A consisted of 3 open-ended questions aimed to stimulate reflection beyond the text (e.g. *What are the on-going changes that affect or worry you most and, in your opinion, what are the changes that will characterize the future throughout the next 20-30 years? What does "making history" mean today, both individually and collectively? What are the differences between "making history" today and at the end of the 90s?*).

2.2. Second phase

The second phase of the pilot study aimed to investigate whether, and how, adults can be guided to understand the conceptual and methodological core of complexity. In the design of these four activities, conceived and developed mainly by EB (Barelli, 2017), we paid specific attention to underlining the characteristic aspects of disciplinary contents, application contexts and forms of presentation of the activities themselves (cfr. Table 1 for an overview).
Despite the variety of issues tackled in the activities, they all have common features that can be recognized chiefly in their design procedure. First of all, a wide literature about complex systems was taken into account in order to isolate the main and most fundamental concepts of the theory. Then, web resources were searched in order to find tools that could be useful to communicate the concepts effectively in an informal context. This research revealed that one of the most popular

tools for introducing complex systems is interactive simulation: this is the reason why the second set of activities contains three different simulations, related to variegated application contexts. Another common feature of our educational materials about complex systems is the important role attributed to mathematical modelling, a fundamental aspect in the whole field of complex systems. Even though we decided not to use a mathematical language in our activities (since our experimentation did not involve students in a curricular context but general citizens with many differences in their mathematical background), we took care of preserving the authenticity of the main mathematical issues when addressing the themes from our educational perspective.
After having located suitable resources on the Internet, we made the conceptual dimension explicit and transformed the tools into completely original activities equipped with purpose, description, and comments. In order to collect data to investigate the development of citizens' knowledge and skills during this phase, every activity of this set ends with the same task: *Summarize (in 3-4 lines) the main message of the activity and the most significant aspects.* We refer to this set of questions as Q_B. The resulting activities have a solid disciplinary dimension, since our purpose was to build as strong a knowledge as possible about the scientific concepts, also maintaining the authenticity of the process of mathematical modelling; at the same time, we devoted special attention to the playful dimension, so that the learning process about the discipline could foster learners' engagement and motivation (van Bilsen, Bekebrede & Mayer, 2010; Chen, 2017).

Table 1. Overview of activities for the second phase of the intervention.

Activity	Disciplinary content	Application context	Form of presentation
Schelling's segregation model	self-organization and emergent properties	sociological modelling	simulation
Emergence in forests	self-organization and emergent properties	ecology, biology	user-adjustable simulation
The Game of Life	self-organization and emergent properties	biological model	simulation
Feedback Ted-Ed lesson	feedback and circular causality	ecology	video-lesson and interactive test

The first activity regards the concept of self-organization as an emergent property of a complex social system. It refers to Thomas Schelling's dynamic model of racial segregation (Schelling, 1971), according to which local interactions (displaying a relatively mild preference for neighbors of similar race) can lead to unexpected and unpredicted aggregate patterns (segregation), without any simple correspondence of individual behavior to collective results. In this first activity, we used a playable simulation, available on an interactive webpage (Vi Hart & Nicky case, A) that guided the users through a story. The protagonists (squares and triangles) share the same environment (a grid in which every element occupies one place); the users can modulate a parameter that indicates the protagonists' preference to live near similar individuals, observing the final rate of segregation of the simulated "social system". The choice of a simulation is not only due to the intrinsic difficulty in manipulating deeply woven variables in complex systems - the term *complex* can be traced etymologically to *cum-plexus*, woven together – that makes practically impossible to study complex

social systems through the experimental technique. The ethical consequences of such an approach were also relevant to us: using a simulation one can implement the equations of the model and replicate, through a specific software, the principal properties, and the dynamics of a social system and, through the controlled manipulation of some reference materials, perform “experiments”.
The second activity has the same conceptual core as the first and is a re-editing of a web resource (Vi Hart & Nicky Case, B): it is a user-adjustable simulation in which the concepts of science of complex systems are applied to the life of a forest. Through the manipulation of the main parameters at the base of their lives (rate of growth of trees, grass, and occurrence of fires), the players become familiar with the concept of emergent property, complex behavior that arises from basic rules, feedback loops and self-organization. These observations reveal the rise of an order initiating from spontaneous behavior, which is not imposed top-down from the beginning like a sort of “town plan”.
An in-depth analysis of the concept of emergence is provided in the third activity with a brief video (Channel 0524432, 2012) that illustrates John Conway’s “Game of Life” (Gardner, 1970). The simulation is a zero-player game, since the evolution is determined by the initial geometrical configuration of “alive” or “dead” cells on a grid, requiring no further input. The evolution is ruled by a few, basic rules that reproduce, in a simplified way, the behavior of biological cells in an environment; for example, they die by overpopulation or underpopulation if they have too many or not enough neighbors. The interest of this game originates from the fact that the system autonomously evolves, showing up surprising geometrical patterns (“still life objects”, “oscillators”, “spaceships”) and providing an example of emergence and self-organization.
The final activity in this set focuses on the concepts of feedback and circular causality as crucial aspects that characterize a complex system. It is organized as a TED-Ed page and is based on an animated video-lesson (Neutel, 2014) in which the topic is positive and negative feedbacks in biological systems; using a musical metaphor, the video provides imaginative tools for thinking about the genesis of self-organization from a complex substrate of feedback cycles. The issue of mathematical description of feedback loops in terms of negative or positive parameters that express the “strength” of the causal link is also addressed in the video. In addition to the general task common to all the activities, this page presents different kinds of questions (multiple choices or open-ended), to boost on-line learning about the topic; moreover, there is a summary about the contents of the video, with guidance for deeper analysis of the topic (links to other Ted-Ed lessons and scientific papers, etc.). A discussion section has also been created, where everyone can leave questions, comments, or remarks.

2.3. Third phase

The last phase of the intervention aimed to investigate through two activities whether citizens are able to use their acquired knowledge of scientific concepts in order to analyze complex problems and, in this way, to develop citizenship skills on the basis of said knowledge. This phase was implemented during a 3-hour meeting in which the participants were divided into 5 groups of four members each; citizens who did not participate in the meeting were given a questionnaire (Q_C) to complete, containing the tasks related to the second activity of this set only. At the beginning of the meeting, before approaching the first activity of the third phase, a common discussion was carried out to highlight and discuss together the main concepts which emerged from the activities of the second phase.

The first activity of the last phase is “The Fishback Game”, a board game for four players about the activity of commercial fishermen, which had the main goal of reinforcing the rejection of traditional linear thinking in favor of a dynamic thought process about feedback mechanisms and the long-term consequences of players’ actions and intentions. In this game, adapted from a proposal found in Pedercini & Burke (2013), the strategy emerges as a characteristic of the group of players: depending on the strategy adopted, either one is the winner, or everyone loses. It is not easy to agree upon the sure strategy to win, but it is rather simple to identify the easiest way to lose: indeed, everyone loses if the players do not consider the feedback loops the game is based on. In this sense, the authentic scientific knowledge about the concept of feedback is supposed to be able to foster the development of a scientific competence (the recognition of loops implicit in the rules of the game) and a citizenship skill too, since the complex system in which it is used is nothing but a model of the real market. Together with the cards and the printed material for the game, the learners-players received a detailed description of the rules and, after a first autonomous round, another sheet containing an outline of two positive and two negative feedback loops that could be identified during play.

The final activity of the pilot study is “Probable, possible and desirable futures for the city of Irene” – this is related to a problem of urban planning, and we invented it inspired by a real situation (Albertazzi, 2017). In a document given to the group, Irene is described as a small town with three commercial companies operating in the food sector; the owners of one of these are interested in enlarging their business and, consequently, the area of their discount store, but this move would require an alteration of the Local Council’s urban regulations as the present Urban Planning Regulations would not allow any possibility of expansion. The problem has been intentionally formulated so as to require the application of a systemic view, as well as the scientific concept of positive and negative feedback to evaluate how the Mayor’s decision today (i.e. whether or not to provide the license to extend the commercial activity) could impact the evolution of the city in the future; for these reasons, the activity is considered as an appropriate context in which the development of an important citizenship skill (i.e. taking decisions about societal complex issues) can be monitored. The activity consists of three parts, wherein the goal is to stimulate reflection on strategies for thinking about probable, possible and desirable futures (Hancock and Bezold, 1994; Voros, 2003). In the first stage, the participants are required to make a decision as though they were the public administrators of Irene, after having carried out an analysis of the present situation and written two probable scenarios for 2025 which illustrate the probable conditions of evolution of the system as a consequence of granted or denied expansion of the discount store. The second part requires them to develop *backcasting* skills (a procedure of thinking that begins with the possible future scenarios and evaluates backwards on the possible paths of events that have determined them) in two given scenarios; moreover, the participants have to identify positive or negative feedback loops that can explain how possible scenarios were arrived at; after having completed this

second part of the activity, they have to confirm whether they would still take the same decision as before. The third and final task about Irene involves developing a desirable scenario for the town, in which the values of individuals have to be taken into account. To collect data about the skills that this activity was able to foster, 5 focus groups were organized during the group discussion about the problem of Irene, asking the citizens which competencies they planned to put into play to resolve the urban planning problem.
The data collection was organized across the three phases of the study as reported in Table 2.

Table 2. Sources of data for a later analysis across the various phases of the experimentation.

Phase of the study	Main data sources
First phase	• 27 questionnaires (Q_A) • 7 interviews
Second phase	• 2 questionnaires (Q_B) • audio-recording of the 20-minute group meeting
Third phase	• audio-recording of a 15-minute focus group • 4 questionnaires from the non-participants at the group meeting (Q_C)

3. Data analysis

The data analysis was carried out with a qualitative strategy, which was iteratively implemented so as to build up an overview of what happened and to interpret it by recognizing criticalities, trends and behaviors during the intervention (Anfara, Brown & Mangione, 2002; Denzin & Lincoln, 2005). The analysis was designed to address the two following research questions:

RQ1. *What is the initial state of scientific and epistemological knowledge of citizens about the concepts of science of complex systems?*

RQ2. *How do citizens use the scientific competences developed by the activities in decision-making processes concerning societal issues? How do they connect and integrate them with other competences, knowledge, and experiences?*

In the current section, the methods and the main results of the analysis are clearly divided into two subsections, one for each RQ.

3.1. The initial state of knowledge

To answer RQ_1, the 34 interviews and questionnaires Q_A of citizens about Bauman's pamphlet were considered as data sources. In order to elaborate a qualitative approach to organize their answers into categories and interpret them, we carried out a triangulation survey with experts (Anfara et al., 2002; Denzin & Lincoln, 2005). Four physicists were involved in the study: three of them are specialists in science of complex systems (Antonio, a professor author of many essays and books about complexity; Nicola, a researcher in Computational Physics; Maria, a secondary school teacher with a Ph.D. in Anthropology and Epistemology of Complexity) while the final participant, Emanuele, is a researcher in History of Physics with an epistemological background[2].

These four experts were asked to read Bauman's text and the questionnaire Q_A that we had given to citizens, after which they were required to comment on the scientific content communicated by the text and, more in general, the whole argumentation developed by the sociologist. A semi-structured individual interview was carried out with each expert.

Although every specialist gave his/her own personal answer in which many idiosyncratic elements can be observed, analysis of the four interviews highlights four recurrent attitudes toward the text: technical, epistemological, personal, and communicative/educational; in Table 3 a short description and some quotes from all the experts are set out. These four attitudes make the specialists' discourses authentically *rich and thick* (Levrini, Fantini, Tasquier, Pecori & Levin, 2015): the four metacognitive dimensions that interlaced in their answers confirmed indeed a deep understanding of the text.

Table 3. The four dimensions that coexist in specialist's discourses.

	Brief description	**Quotes**
Technical dimension	Recognition and critical analysis of scientific terms and concepts in the text	*"Complexity arises from the inadequacy of a unified description, from the ability to privilege different variables, different indicators, different space-time levels, and the relationship between these different worlds we create through descriptions."* (Antonio) *"The main meaning of Laplace's claim lies in the fact that the evolution of a system is determined; studying the evolution of a system means defining the initial conditions and the laws that govern it, the differential equations whose integration allows to determine the trajectories and so the evolution of the system. This is, as Baumann says, «a pre-determined future determined»"* (Maria) *"The concept of turbulence is correctly connected* [in the text] *to deterministic chaos and refers to systems with an extremely limited time horizon.* […] *There is a strong distinction between possibility and plausibility."* (Nicola)
Epistemological dimension	Recognition of the metaphorical and epistemological meaning of scientific terms, as well as the emerging view of nature of science	*"According to Bauman* [irreversibility] *is a property: «physics has proved that it is an ontological property of the world."* (Antonio) *"What science or scientific vision is there at its base?"* (Emanuele)
Personal dimension	Recognition of the sociological thesis and personal evaluation of the argumentation	*"The point is to learn how developing formae mentis* [mindset] *to avoid being inflexible toward eventualities. […] The risk is to vehicle the message that scientific uncertainty causes a global uncertainty in society and influences what happens at every level."* (Emanuele) *"It would be a good idea to encourage reflection to look for more information and widen horizons."* (Nicola)

[2] All the names in the transcripts are gender-indicative pseudonyms.

Communicative educational dimension	Recognition of the general goal of the text and suggestion of inputs to strengthen its message	*"In the section related to mixophilia and mixophobia, I read between the lines some characteristic elements of complexity that could be made more explicit, but I understand that the goal of the author was surely different, more sociological."* (Maria)

To develop the analysis of citizens' interviews and questionnaires, we searched for the previously identified dimensions in their answers. The result was that, contrary to the richness and in-depth quality of the specialists' discourses, the citizens focused on only one perspective in their answers; moreover, the communicative-educational dimension was missing in the citizens' answers. In Table 4 the three types of answers, the number of people (out of 34) who displayed each attitude, their description and some quotes are set out.

Table 4. The three types of citizens' answers (out of 34 total answers).

	Brief description	**Quotes**
Technical answer (4 answers)	Focus on scientific terms from a technical perspective (correct basic definitions; scientific dimension disconnected from the sociological thesis)	*"Laplace and the determinists* [...] *believed that, in the universe and in life, nothing is left to chance, everything is governed by precise laws, everything has a cause and an effect: if we understand the laws, we can come to the certain knowledge of the future."* (Paolo) *The world of becomingness, characterized by turbulence and probability is introduced… a world that irreversibly evolves not only according to clear and established laws, but also by virtue of random elements. Randomness is its characteristic, while causality is less defined, since it can arise from several unpredictable factors."* (Carlotta)
Epistemological answer (2 answers)	Recognition of scientific terms and their epistemological meaning (correct explanations; understanding of the role of science within the sociological argumentation)	*"I agree with Bauman's interpretation about the complex world... The fact that we cannot get rid of the uncertainty of the future and at the same time we know that even the action of an individual can provoke epochal changes is an extraordinary thing!"* (Marinella)
Personal answer (28 answers	Common sense- based answer (missing recognition of the scientific origin of terms like probability, uncertainty, system; approach guided by personal experience or good sense)	*"I would say that the significance of Laplace's claim is stimulating, because uncertainty, in the right measure, is something that stimulates us to search for the condition of certainty, which, in my opinion, even when we think we have achieved it, must and can always be improved"* (Martina) *"The seductive view* [of Laplace's claim] *is when, having surpassed the uncertainty, the whole arouses a general well-being. Conversely, the vision is less seductive when it creates a war."* (Grazia) *"The world of becomingness is characterized by the fact that the world is no longer ordered by imposed rules, structures and laws."* (Livio)

The predominance of answers based on common sense is evident; regarding the four technical answers, it is important to mention the fact that they come from four professionals with a technical-scientific education (e.g. engineering). A comment is provided in the discussion of the results.

3.2. The competences put into play

To answer RQ_2 and study the correlation between scientific skills developed through the second phase of the intervention and citizenship skills displayed in the third phase, we considered as data sources the audio-recordings of the group discussion about the second set of activities, and questionnaires Q_B and Q_C of the focus groups about Irene. Four types of correlation have been recognized and identified in terms of alignment between scientific/technical competences and decision-making competences:

- **successful alignment**: the scientific concepts (e.g. feedback, equilibrium) are used in non-scientific contexts to analyze a situation and to evaluate future scenarios.

  If the number of enterprises grows, as well as the agenda of cultural events, families become richer and attract other families and, thus, other enterprises... this is a positive feedback because it is a self-perpetuating mechanism! (Cristina, 46)

- **semi-successful alignment (awareness)**: there is an explicit acknowledgment of the distance between “emotional” ways of thinking about citizenship issues and scientific competences which have not been consciously acquired.

  I am totally disengaged from science and I don’t have any skills, but what I use to reason and decide is the emotional component and the idea of a sort of equilibrium. (Lucia, 52)

- **unsuccessful alignment (no citizenship skills)**: explicit refusal to use hard scientific knowledge acquired during the second set of activities to address a “soft” problem of urban planning, where there is no exact solution.

  I have technical competencies but, as a specialist, I am of service to policy makers and their political decisions. […] I cannot decide with technical competencies about political problems. (Carlo, 65)

- **unsuccessful alignment (common sense)**: absence of scientific competences and use of an approach based on common sense when the problem of urban planning is addressed.

  I don’t have any technical skills but I reason with common sense to evaluate the pros and cons of a decision and to find the best solution for everyone. (Marco, 40)

The latter attitude was predominant; we can conclude that, for these citizens, the second set of activities was not effective in building a significant knowledge about the science of complex systems.

In particular, they encountered difficulties in understanding the correct meaning of scientific terms (e.g. *negative* and *positive* feedback loops were perceived as *bad* or *good* mechanisms respectively, according to their common meaning in everyday language) as well as problems in grasping the methodological and epistemological value of simulations not as mere games but as tools for approaching the science of complex systems. Yet, the presence of successful cases represents a strongly positive sign since the activities were very innovative and they have a large margin for improvement. The most worrying result is the third type of reaction that, as we will describe more comprehensively in the next section, comes from scientifically educated citizens who did not feel comfortable in applying hard knowledge to "soft" and citizenship problems.

4. Discussion of the results

The citizens' initial state of knowledge about the concepts of science of complex systems was not only very patchy from a theoretical point of view but also revealed a lack of explicit reflection on the epistemological contribute of science in general. This is particularly evident in the answers provided by professionals with a technical-scientific education: they gave correct technical definitions of the scientific terms used in Bauman's argumentation, but this did not lead them to reflect on the methodology and epistemology of the scientific content. An epistemological perspective, even though quite accurate from a technical point of view, can be recognized in just two cases where the citizens had no scientific education at all. The ample frequency of answers based on common sense bears witness to the discomfort of citizens concerning a text that was perceived as "too scientific" and therefore out of their reach; this is confirmed by the absence of educational or communicative perspectives in their answers. While the specialists, having understood the content of the text from scientific and sociological perspectives, felt authorized to assume a critical point of view towards the text, expressing opinions about its argumentative strengths and weaknesses, the citizens did not feel qualified to do so, often underlining their own inadequacy in reading such kinds of text. The triangulation with experts also allowed us to identify a common characteristic of all the citizens' answers: in approaching the text, they did not integrate different dimensions (correct conceptual understanding, epistemological critique and personal reflection and interpretation) but remained anchored on only one of these aspects. This attitude contrasts with the richness of experts' discourses in which they display an acquisition of content knowledge which is organized in harmonious ways, through the overall epistemological perspective and the personal evaluation of the text in general, reflecting a deep understanding of the topic. This difference we have observed is consistent with research on expert and novice differences in general (Chi, Glaser & Farr, 1988; Larkin, McDermott, Simon & Simon, 1980; NRC, 2000; Wu, Wen, Chen & Hsu, 2016) and about science of complex systems in particular (Hmelo-Silver & Pfeffer, 2004; Jacobson, 2000, 2001; Jacobson & Wilensky, 2006).

The second important finding concerns the effectiveness in some cases of scientific activities in developing citizenship skills (e.g. taking into account multiple perspectives and joint participation in public decisions) that were supposed to be fostered by our activities along the intervention.

Although not a majority, the successful cases of alignment between scientific-technical competences and decision competences show that it is possible to design activities based on authentic scientific concepts in order to develop citizenship skills. Such cases of successful alignment showed, in their answers, the same pattern of reasoning: i) decoding of the scientific apparatus of the science of complex systems; ii) application of those scientific concepts to personal contexts; iii) use of those concepts for the analysis of a complex civic situation and to take the decision. This pattern is based, first of all, on the traceability, in the citizens' discourses, of epistemological ideas and scientific concepts typical of the science of complex systems. For instance, a renounce to linear causality can be observed in favor of an embracing of circular patterns of complex relationships between causes and effects, showed in the use of feedback loops to reason about future scenarios of the town Irene. This is an example of how hard-scientific skills (e.g. the ability to recognize a feedback loop) were applied in a context that goes beyond science and, in particular, to analyze an urban problem and make a decision on that, that are citizenship skills.

We consider significant also the attitude of semi-successful alignment. These citizens, at the end of the third phase of the intervention, clearly recognized the value of the scientific concepts and the related epistemological ideas, even if they considered the level of knowledge they reached not solid enough to use it for reasoning about a complex problem. We can interpret the data concerning patterns of successful and semi-successful alignment using our theoretical framework, as follows.

The main concepts of science of complex systems (non-linearity, high sensitivity to initial conditions, feedback loops, emergent properties), grasped thanks to the activities of set B, provided those citizens with lenses to look at complex scientific, environmental, societal, and economic phenomena. For example, the reported quote by Cristina shows that the crucial term "feedback" was exported from the native scientific field to the evaluation of future scenarios for the town of Irene, recognized as a complex system; in other people's discourses, similar sentences refer to the concept of "equilibrium". As we anticipated in our theoretical framework, considering a specific system as complex requires it to be approached with an appropriate attitude and a suitable conceptual, technical, and epistemological framework. In these cases, citizens showed to have started to adopt this approach in their ways of reasoning about problems.

Finally, the activities triggered interesting social dynamics that were appreciated by citizens: most of them recommended repeating the experience in the form of training activities in town councils, since they recognized and appreciated their value as tools for developing citizenship skills.

Alongside these elements of success, the study also revealed some weaknesses. Some citizens, in the cases of unsuccessful alignment (no citizenship skills), explicitly refused to use scientific knowledge to address a problem of urban planning. This problem was not recognized as a complex problem that requires to be addressed with a new epistemological attitude inspired by the conceptual apparatus of the science of complex systems. As we have pointed out in our theoretical framework, this can be interpreted as an example of the gap between science and citizenship (Jacobson & Wilensky, 2006).

The numerous cases of unsuccessful alignment (common sense) confirmed the well-known difficulties in learning about the basic concepts of the science of complex systems and their counterintuitive character (Casti, 1994; Wilensky & Resnick, 1999): the common sense remained, in

these cases, the only basis for their reasoning about complex problems. A similar difficulty can be traced in the cases of semi-successful alignment, since the citizens were aware that they had not completely understood the scientific concepts and then, continued to use their common sense. These cases indicate that our educational approach has to be improved and reinforced in order to contribute, in a more significant way, to fill the mentioned gap between science and citizenship.
As another criticality of the intervention, the activities of the third phase (The Fishback Game and the Town Irene) activated forms of resistances from the citizens with a technical-scientific education, since the activities conflicted with their image of "science for specialists"; even the simulations, largely used in the second set of activities, were not perceived in some cases (particularly by older individuals) as authentic scientific tools used to make visible the mathematical modelling of the real situation but only as mere games. The playful dimension, which we predicted able to foster engagement and interest, resulted in distancing the older participants in the study.

5. Conclusions

Our work in the pilot study presented above addressed the issue of scientific citizenship, providing an example of how appropriate scientific and mathematical contents typical of science of complex systems can be reconstructed from an educational perspective, taught, and organized in the form of activities aimed at developing citizenship skills.
Approaching complex systems requires an intrinsically interdisciplinary modelling that moves from the mathematical equations to the physical, biological, economic, and social situations; this modelling makes large use of tools, such as simulations, which are becoming increasingly important at decisional, economic, and political level, but are very rarely taught at school and, usually, are not part of the school education of current adult citizens. In our intervention, the explicit reflection on disciplinary concepts like equilibrium, system, feedback, and causality allowed in some cases a more conscious approach to a civic and political problem, as urban planning is.
The innovative contribution of this chapter can be traced mainly in its approach: the idea that STEM disciplines themselves may have a transformative power to encourage citizens to develop skills. This process starts from teaching the core ideas and ways of thinking of the science of complex systems (non-linearity of the models, systemic vision, circular causality, concept of self-organization as an emergent property), without getting trapped in technical and mathematical aspects: this approach helped the citizens to interpret and manage complex social dynamics in an authentically complex way, both from a conceptual and an epistemological perspective. As we already mentioned in the theoretical framework, our approach is different from the classical ones in which there is more emphasis on the methodological aspects of science and less importance is given to the conceptual knowledge (Osborne, 2010): we have not only given a general idea of the scientific methods, but we have introduced also specific scientific concepts as bases to scaffold citizenship skills. Even though this approach showed some criticalities, it demonstrated to have some potential.
The cultural and political value of the experimentation was recognized by almost all the citizens; in particular, one council member participant in the study suggested that the mayor *"organize the same course with the whole municipal council, because it was a wide-ranging project for the*

community: a project in which the community is reinforced and democracy realized" (Franco, 54). For these reasons, we consider this study as a basis for further reflection on the potential relevance of STEM disciplines in sustaining an informed and, thus, healthy, and vibrant democracy (Millar & Osborne, 1998), as required by many reports in the field of citizenship education.

The results of this pilot study led to a revision of the activities (specifically in the second and third phases of the intervention) for a second pilot study that involved voluntary secondary-school students as part of a project (*National Scientific Degree Project*) hosted by the Department of Physics and Astronomy of Bologna. This context allowed a more intensive focus on the technical contents of the discipline of complex systems; therefore, the second set was re-designed framing the activities within a lecture in which the mathematical and formal dimension was also introduced through the Lotka-Volterra predator-prey model (Volterra, 1926). The third phase of the intervention was also modified, in that the wide span of citizenship skills was restricted to a specific set of competencies of imagination and projection into the future: future cities, future professions, future societies, future worlds. These skills, within the I SEE European Erasmus+ project (www.iseeproject.eu), have been classed as future-scaffolding skills. The results of this pilot study were particularly successful (Barelli, 2017).

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Chapter 2 - Explaining complex systems through computational simulations[3]

The science of complex systems can provide not only scientist, but also professionals, policy-makers, and citizens, with thinking resources to interpret and understand most of the modern global challenges. In this field, the widespread use of computational simulations, that are neither theoretical instruments nor laboratory experiments, has been contributing to the widening of the scientific skill gap between experts and citizens. The pilot study we present in this contribution aims at investigating high school students' approaches towards simulations of complex systems, by searching for the criteria they use to evaluate their explanatory power and the reliability of their results. Preliminary analysis of the paired interviews has shown that (1) rarely students are able to elaborate explanations of the simulated complex phenomena, and (2) their critical attitude and trust towards simulations are strongly affected by their epistemological background. We argue that these findings deserve to be furtherly investigated, to understand in more details the sources of students' difficulties in recognizing the epistemological and methodological value of simulations for scientific research and practice.

1. Introduction

In an increasingly complex world, our society is facing big global challenges – e.g. global warming, migrations, radical changes in the labour market dynamics, world populations growth – and most of them need STEM (Science, Technology, Engineering and Mathematics) knowledge and competences to be tackled and understood (UNESCO, 2015). Indeed, innovations in the STEM research and application fields influenced so much the society in the last decades that, in order to

[3] The contents of this chapter are the object of a paper entitled "High school students' epistemological approaches to computer simulations of complex systems" (Barelli, Branchetti & Ravaioli, 2019) which is based in turn on the homonymous extended abstract accepted for an oral presentation at the GIREP 2018 Conference (Ravaioli, Barelli & Branchetti, 2018) and a preliminary work selected for an oral presentation at the MusT 2018 Conference "Models of Explanation" (Barelli, Branchetti & Ravaioli, 2018). A presentation of the findings of this study was also included in the communication at the SIF 2019 Congress (Barelli, 2019).

rationally manage such issues, it is necessary to own specific thinking resources and to be aware of the connections between STEM and society, both in terms of possible dangers and of opportunities (Branchetti et al., 2018). By contrast, we are facing a paradox (Tola, 2018): never before in human history there have been so many scientists developing so many analytical tools, but they often do not reach the working knowledge of professionals, policymakers and citizens. Although they must deal first-hand with the challenging social and global problems, a growing distrust toward science and scientists has been reported (Lewandowsky & Oberauer, 2016). In fact, the analysis and understanding of these issues would require scientific competences coming from the science of complex systems (Batty, 2016). The widening gap between the expert knowledge of scientists and that of common citizens (Jacobson & Wilensky, 2006) is not only due to the conceptual difficulties of the topics but also to the epistemological and methodological novelties they introduce (Barelli, Branchetti, Tasquier, Albertazzi & Levrini, 2018). Indeed, complex phenomena like climate change cannot be investigated with the traditional experimental method (Pasini, 2015), that is why most of the projections and elaborations of future scenarios that – should – inform policy-makers decisions are not based on experiments but rather on computer simulations. Although they have progressively flanked theories and laboratory inquiry in research practice and ranked as the third pillar of science (Parisi, 2001; Galison, 2011), simulations are usually not part of high school curricula. Indeed, even if many multimedia interactive tools have been introduced in the classrooms (e.g. the ones produced by PhET (https://phet.colorado.edu/) to illustrate classical models like ideal gases, friction and electric circuits), they are rarely simulations of authentic complex systems that cannot be investigated with the traditional experimental method.

Driven by these motivations, we decided to investigate the problem of high school students' trust towards computer simulations of complex systems and to look for implicit or explicit criteria they use to evaluate their explanatory power and the reliability of their results. This research problem lays its foundation on results of researches in STEM education about complex systems, i.e. the novices' difficulties in interpreting their simulations (Penner, 2001), in formulating explanations about them (Perkins & Grotzer, 2000), and in dealing with causal reasoning (Viennot, 2001). In this chapter, we present: i) the framework we chose for formulating our research problem, making explicit the factors we considered *a priori* relevant; ii) the methodology of the research we used in our pilot study, discussing its strengths and weaknesses; iii) some preliminary results that confirmed some of our hypotheses, but also led us to question the validity of some of other hypotheses and to refocus the problem.

2. Research framework

2.1. The science of complex systems, its relevance today and the difficulties in its learning

Since the second half of the 20th century, a new field of study has grown within the scientific community: the science of complexity. This discipline studies the so-called complex systems, constituted of a set of individual elements which, interacting with each other and with the environment according to non-linear relationships, give the resulting systems some properties that the classical ones do not have (Cilliers, 1998). The main traits of most complex systems can be summarized in the following list: i) non-linearity of the equations that describe the macroscopic variables and of the rules for the local interactions among the agents; ii) high sensitivity to initial conditions or “butterfly effect”; iii) presence of feedback loops; iv) appearance of global properties that cannot be deterministically ascribed to the local rules which the individual agents obey but emerge from the self-organization of the system.

From the 1970s, many systems have been studied and modelled as complex, within a very wide range of disciplinary fields: to report few examples, cells, human brain, crystalline solids, social systems, cities, and climate are considered and have to be studied as complex systems. Because of the increasing relevance of issues like climate change and urban planning at many decisional levels, the perspective of complexity is becoming more and more important to be embraced by the people involved in decision-making activities (Batty, 2016). While this can be stated as an urgent goal to be achieved, the educational research about complex systems has shown strong and resilient difficulties in learning about complex systems, mainly due to the conflict between new complexity-related concepts and commonly held beliefs or learners’ prior experience (Casti, 1994). The main conceptual difficulties can be summarized in the following two points: i) difficulty in giving up a sense of centralized control and deterministic causality in favour of descriptions involving self-organization, stochastic and decentralized processes (Feltovich, Spiro & Coulson, 1989); ii) difficulty in renouncing the conception of a linear relationship between the size of action and the corresponding effect, accepting the butterfly effect (Casti, 1994).

2.2. The simulations for the study of complex systems

Together with the set of new concepts introduced in the scientific community, the science of complex systems has developed specific methods of analysis, including computational simulations. Going beyond the traditional laboratory experiments and theories, simulations can be considered the third important tool of science (Parisi, 2001). When a simulation runs on a computer, it gives rise to empirical predictions that derive from the theoretical mathematical model of the phenomenon under exam, and it works as a virtual laboratory in which, just as in the real laboratory, the researcher monitors the phenomena under controlled conditions, manipulates these conditions and discovers the consequences of such manipulations. The simulations are becoming more and more important not only for the scientific community that uses them as a mean of inquiry but are also at the core of the communication of the scientific results to policymakers and citizens and are currently used to support policy formulation (Grüne-Yanoff & Weirich, 2010).

Philosophers of science have offered a number of definitions of simulations. For the purpose of this chapter, we refer to the following one: “System S provides a simulation of an object or process B just in case S is a concrete computational device that produces, via a temporal process, solutions to a computational model that correctly represents B, either dynamically or statically. If, in addition, the computational model used by S correctly represents the structure of the real system R, then S provides a simulation of system R with respect to B” (Humphreys, 2004). We think that this definition is particularly helpful in our framework because it allows to distinguish between three

different levels: the real system (R), the model of object or process (B) and the simulating system (S). Even the categorization of simulations can be performed in many different ways, according to different criteria; following (Grüne-Yanoff & Weirich, 2010), we can distinguish equation-based simulations and agent-based ones. The first are simulations describing the dynamics of a target system with the help of equations that capture the deterministic features of the whole system: a set of differential equations is used to derive the future state of the target system, modelled as an undifferentiated whole, from its present state. The agent-based simulations, at the opposite, lack an overall description of the macro properties of the system and simulate it by generating its dynamics through the imitation of its micro constituents that behave as dictated by local rules.
Simulations are thus crucial in dealing with complex systems but their interpretation as authentic scientific tools is a delicate point. Many criticalities have been individuated from the literature in science education exploring novices' attitude toward simulations of complex systems; we summarize two of them. First, while experts are able to move from the agent-based description to the aggregate-systemic reasoning and vice versa depending on the target of the analysis, the novices often develop linear agent-to-aggregate inferences, contrasting with the authentic disciplinary concepts related to complex systems (Jacobson, 2001). The second criticality has been highlighted in a study carried out with adult citizens in a context of citizenship education (Barelli et al., 2018): many participants harboured resistance when dealing with simulations that were perceived as mere games and seemed not to grasp their methodological and epistemological value.

2.3. Scientific explanations through simulations

The sciences use simulations for multiple purposes; among their uses there are proof, prediction, policy formulation and explanation of complex phenomena (Grüne-Yanoff & Weirich, 2010). The issue of explanation in general is widely explored and precisely conceptualized by the philosophers of science. Conversely, within the science education community, there is much discussion about this issue with a still little consensus about the nature of explanation itself (Braaten & Windschitl, 2011). Indeed, the literature in science education refers, mostly implicitly, to many different conceptions of explanation. A synthesis of them is provided in (Braaten & Windschitl, 2011):

- *Explanation as explication*: explaining consists in providing clarification for the meaning of a term or explicating a reasoning about a problem.
- *Explanation as causation*: explaining consists in establishing a causal account referring to the mechanistic properties of the phenomena (mechanistic explanation), to the physical laws the phenomenon has to follow (covering-law explanation), to the final goal the phenomenon has to realize (teleological explanation) or, when humans are involved in the object of the explanation, to the intentions of the individuals to reach a goal (intention-based explanation).
- *Explanation as statistical justification:* explaining consists in justifying phenomena by using statistical-probabilistic analysis of large data sets.

For the purposes of this chapter, we consider only the second and the third types mentioned above as proper scientific explanations. Going deeper into the causal explanations, research in science

education has shown that the mechanistic explanations are those that most foster students' sensemaking about phenomena (diSessa, 1993). Indeed, it has been proved that, when students are able to provide a mechanism to explain a causal relation, they express more confidence in the validity of the causal relation itself (Schauble, 1996). The mechanistic explanations can be recognized by tracing the structural components of mechanism: description of the target phenomenon; identification of setup conditions, entities, activities, properties of the entities; chaining backward and forward; analogies (Russ, Scherr & Sherin, 2012; Kapon, 2016).
According to these results, we considered the possibility of understanding the mechanism and producing causal explanations as a potential source of reliability for students dealing with computational simulations. In general, since explanation is strongly linked to sensemaking (Kapon, 2016) and causation, we hypothesized that the trust or mistrust of students in simulations as scientific tools could rely, at least partially, on the feeling that it is possible and meaningful to use them to explain real phenomena.
In most of the applications of simulations to explanations of complex phenomena, it has been noticed a gap between the simulation outputs and the model (Jebeile, 2018). This gap is largely due to the fact that computer simulations are epistemically opaque (Humphreys, 2004), which means that they are sorts of thought experiments in which the consequences follow from the premises, but in a non-obvious manner which can be revealed only through systematic inquiry (Noble, Bullock & Di Paolo, 2000).

3. The pilot study: context, design, and data collection

The goal of our work is to investigate the problem of high school students' trust toward computer simulations of complex systems and to look for the implicit or explicit criteria they use to evaluate their explanatory power and the reliability of their results. In our pilot study we were particularly interested in identifying the epistemological issues that the students mentioned when formulating explanations and reasoning about simulated phenomena and in investigating the factors that could influence students' attitudes toward computer simulations in terms of trust.
The pilot study consisted in performing 13 semi-structured paired interviews; we chose this method because we were interested in the interactions among students, that are frequent and rich when the pairs consist of schoolmates (Wilson, Onwuegbuzie & Manning, 2016), as it was in our case. During the interview, the students were asked to discuss about four different computer simulations of complex systems, responding the questions of our protocol. We included an interactive multimedia tool about ideal gases in the set of simulations presented to the students in order to compare the answers in the classical and complex cases.
The group of people involved in the qualitative study consisted of 26 volunteer students (12 males, 14 females), aged 17-18, of 5 different high schools in Emilia-Romagna, Italy. They were recruited by their physics teachers, who collaborate with the research group in STEM education at the University of Bologna. The majority of the students (24 out of 26) were attending scientific lyceums; only two of them were attending a linguistic lyceum. The science of complex systems was not part of the background of any student, since ministerial programmes, in Italy, do not include such issues.

We collected data through the interviews and then we carried out a qualitative analysis of four selected cases, as we will explain in the following section. In the followings, we provide a brief description of each simulation and the main features of the model they refer to; for the purpose of the analysis we report in the next section, here we focus especially on two simulations of complex systems and provide only few details for the others. Then, we describe the structure of the protocol and some of the questions asked to students.

3.1. The models and the simulations

3.1.1. Social segregation

The first simulation is built on the basis of the Schelling model of segregation (Schelling, 1971). We decided to include it in our study since it can be easily described but displays one of the most characteristic features of complex systems: the emergence of global properties of the whole system starting from local rules for the minimal sub-components which, namely, self-organize. In this model, there are two types of individuals who tend to move if they find themselves in regions where the other type is present over a certain percentage (1/3 default). These agents, that are not created nor destroyed during the evolution of the system, evolve according to a simple rule on the basis of their level of satisfaction, which in turn is determined by the makeup of their neighbourhood. Starting from an initial mixed population, the time evolution leads to an environment in which there are separate groups of individuals of the same category: an even slight homophilic bias is sufficient to cause wholesale segregation of the two types of agents. The simulation we have chosen for this model is an agent-based one (https://ncase.me/polygons/) where the agents (squares and triangles) share the same environment (a grid in which every element occupies one place). The user can modulate a parameter that indicates the protagonists' preference to live near similar individuals, observing, in a graph, the final rate of segregation of the simulated social system. Changing the percentage of preference, higher levels of segregation display, even if, over a certain threshold, it can be seen that the model does not converge, and the agents continue to move "forever". In Figure 1 we report the initial state and the final configuration in a run of the simulation.

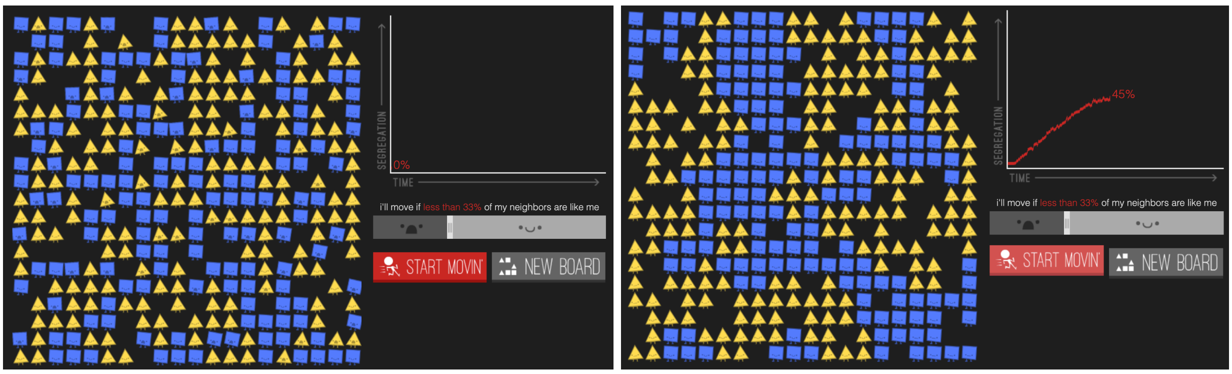

Figure 1. Initial state with randomly distributed agents (left) and final configuration with segregated agents (right) displayed with an agent-based simulation of the Schelling's model.

3.1.2. Predator-prey interaction

The second simulation implements a model of an ecological complex system: the Lotka-Volterra model (Volterra, 1926). It consists of a pair of first order, non-linear, differential equations used to describe the dynamics of biological systems in which two species interact, one as a predator and the other as prey. By numerically integrating the equations, the solution of the model is periodic and can be interpreted in terms of circular causality. The periodic growth of the prey population is followed by the growth of the predator population; the consequent reduction of prey population causes a reduction of predator population, since there is less food to eat; this reduction of predator population lets the prey population grow and this cycle continues forever. Most of the Lotka-Volterra model simulations are equation-based; the output of this type of simulations is a graph showing the periodic evolution of the system dynamics. Since previous studies showed that some students had difficulties with this genre of simulations, when requested to act on the values of the parameters and to interpret the changes in the graph (Barelli, 2017), for this study we decided to use an agent-based simulation of the same model (https://www.eduweb.com/portfolio/studyworks/predators8a.html)[4]. In this simulation, there are two types of agents that populate a grid – the Canadian lynxes (predators) and the snowshoe hares (prey) – and interact according to a set of few rules (e.g. if a lynx does not have at least three hares among its nearest neighbours, starves and dies; if a hare escapes the lynxes, it survives and reproduces once). The user observes the changes in hares and lynxes' populations in the grid and after thirty generations, is displayed a graph representing the periodic evolution of the populations. The grid and the graphs are reported in Figure 2.

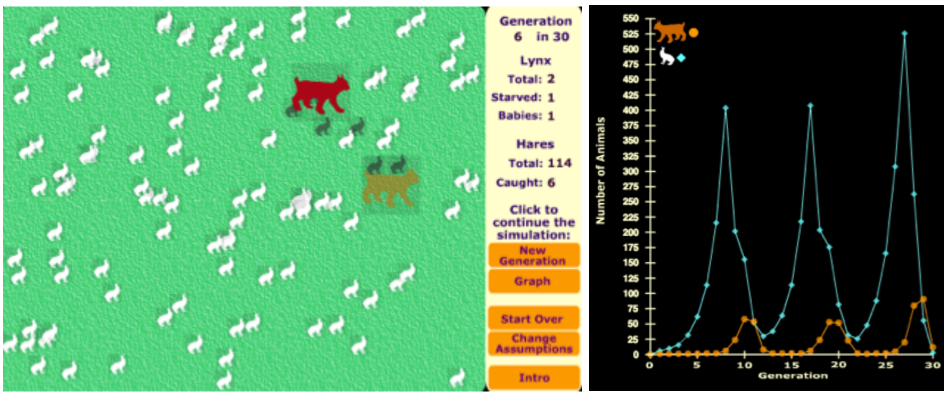

Figure 2. Grid with interface (left) and graph (right) for the number of lynxes and snowshoe hares obtained with the Lotka-Volterra agent-based simulation.

3.1.3. Ideal gases

The third simulation refers to the model of ideal gases and the kinetic molecular theory. With this simulation, developed by the PhET (https://phet.colorado.edu/en/simulation/gas-properties), the user can pump gas molecules to a box and see what happens by changing the volume, furnishing or

[4] At the date of submission of this dissertation, the link to the resource powered by EduWeb results no more active due to the discontinuation of the Adobe Flash Player plugins.

subtracting energy in the form of heat, changing gravity; temperature and pressure can be measured, and the properties of the gas can be investigated. The interface of the simulation is reported in Figure 3.

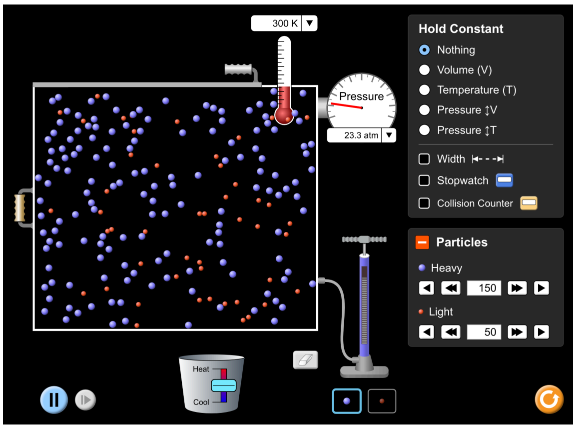

Figure 3. Interface of the PhET simulation for ideal gases' properties.

3.1.4. Global warming

The last class of models we considered are the climate models and, in particular, their estimations for the possible changes in the temperature patterns throughout the 21st century. The models we refer to are those used in the last report from the Intergovernmental Panel on Climate Change (IPCC, 2018) to formulate predictions about how the Earth might respond to four different scenarios of how much carbon dioxide and other greenhouse gases would be emitted into the atmosphere. For our study, being the simulations very technical and difficult to experience by a secondary-school user, we chose to include a video that shows the changes in temperature and precipitations through the 21st century, on the basis of the IPCC models (https://www.youtube.com/watch?v=d-nI8MByIL8&feature=youtu.be). In Figure 4 we report two snapshots of the video, one for short-term and long-term projections.

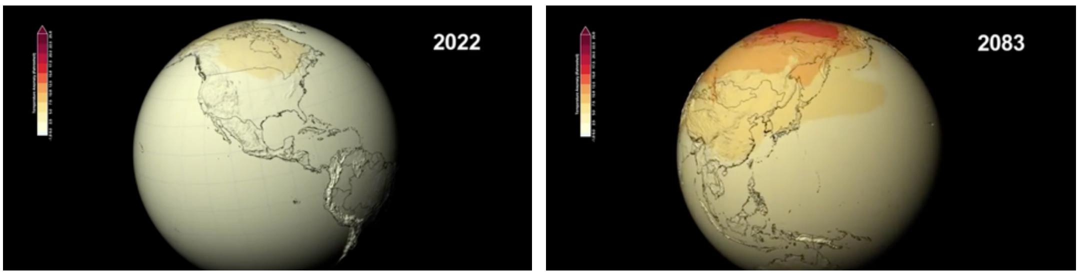

Figure 4. Short-term (left) and long-term (right) scenarios for global temperature according to the IPCC projections.

3.2. The interview protocol

At the beginning of the interview, the interviewers described the main characteristics of each simulation to the pair of students, then they asked them to explore each simulation, by watching the space-time evolution of the systems and by modifying the values of the possible parameters.

The interview protocol consisted of five sections, the first four designed to investigate different dimensions of the students' reasonings on simulated phenomena that could influence their trust and the last one to explicitly ask the students what affected their perception of trust/mistrust. More specifically, the sections aimed at making the students: i) observe and describe the "surface" of each simulation, identifying the fundamental elements represented and those in the background; ii) attempt an explanation of a specific simulated phenomenon; iii) carry out a meta-reflection about the meaning of explanation; iv) compare the output of the simulation and the data obtainable from a laboratory experiment; v) express their perception of trust and confidence about the use of simulation for addressing concrete real-world problems. In table 1, we report some questions for each section.

Table 1. Sections of the interview protocol and some examples of questions.

Section of the protocol	Examples of questions
Description of the surface of the simulations	Identify relevant and non-relevant elements, changes, processes, user's way of interactions. Identify which elements are models and which are elements of reality.
Explanation of simulated phenomena	Explain this phenomenon. How does this simulation help you explaining the phenomenon? - The environment is divided into quarters and segregation is realized. (Social segregation) - There are cyclic and periodic evolutions for the numbers of prey and predators. (Predator-prey interaction) - Given a certain state, during a volume compression, the temperature can be kept constant. (Ideal gases) - In 2089, the highest temperature anomaly, with respect to today, is going to be at the poles. (Global warming)
Meta-reflection about "explaining"	What are the differences, in your opinion, between describing, interpreting, and explaining a physical phenomenon? Are there any "whys" you can answer using this simulation? How are determinism and uncertainty related to this simulation?
Simulations, laboratory experiments and reality	Which is, in your opinion, the relationship between the simulated phenomenon and the data that can be obtained with a lab experiment? Does the simulation explain a real phenomenon?
Perception of trust	Would you trust the results of the simulation to deal with a real problem?

4. Research methodology and research question

The data analysis was carried out with a qualitative methodology, through a theoretically-oriented iterative process of analysis and interpretation, where the hypotheses formulation was progressively refined through an enlargement of the empirical base, until theoretical saturation was reached (Denzin & Lincoln, 2005). Focusing with respect to the wide spectrum of topics and simulations presented above, the analysis was designed to address the following research question:

RQ1. What factors influence students' attitudes toward simulations of complex systems and their level of trust?

In this preliminary study, we focus on two interviews (four students) and we compare them. All the students attended the same type of school – scientific lyceum – 13th grade, but a couple – Elizabeth and Anthony[5] – had a physics teacher who, across the whole curriculum, systematically stressed the epistemological role of models in science, while the other two students – Lily and Evelyn – did not have any specific "epistemological education". After a preliminary reading of the whole dataset of transcripts, we selected these two interviews because the first one was particularly rich from an epistemological perspective, while the second one seemed to represent the majority of the interviews. As a general comment, to answer our research question we looked at the complete transcript of each interview, since the nature of students' reasoning did not emerge by analysing isolated sentences.

According to the research framework outlined above, we hypothesised that the recognition of the explanatory power of the simulations could influence the perception of students' trust toward them. That is why the first step of the data analysis consisted in the exploration of students' explanations; to do this, we considered the framework outlined in 2.3 to distinguish between descriptive explications and proper explanations. In order to make this distinction more operational and use it as a lens to analyse students' discourses, we formulated five *a priori* statements about the four simulations. They were intentionally prepared as an explication and four different causal explanations (mechanistic, covering-law, teleological and intention-based). Table 2 includes the statements about the phenomenon of social segregation in the simulation of the Schelling's model.

Table 2. A priori explanations for the phenomenon of social segregation claimed in the second part of the interview *("the environment is divided into quarters: segregation is realized")*.

Explication		The squares and the triangles become divided in groups of the same type.
Explanations	Mechanistic	If at least the 33% of the nearest neighbours are of the same type, the individual is happy and does not move; otherwise, the individual tends to move and reach another position in which he has at least the 33% of neighbours like him; now we evaluate the satisfaction of another individual and he moves in the same way: he will be surely happy if he move near an aggregate of similar individuals. Continuing this way, it results that individuals are "attracted" by group of similar individuals: the so-called segregation is realized.
	Covering-law	The environment becomes segregated because the individuals have to satisfy their law of preference: having the 33% of their nearest neighbours similar to them.
	Teleological	The environment becomes segregated because this is the goal the individuals have to achieve.
	Intention-based	The environment becomes segregated because every individual wants to stay with similar ones.

[5] To preserve anonymity, all the students' names used in this chapter are gender-indicative pseudonyms.

Not all these explanations are considered acceptable by scientists nowadays: in particular, the teleological and the intention-based one hide the false assumption that local rules directly lead to corresponding global behaviours. In this phase, we were also interested to check the presence in the interviews of the structural components of mechanism (Russ, Lee & Sherin, 2012; Kapon, 2016), in order to investigate if and how they contributed to the development of causal explanations.
The second phase of analysis aimed at investigating if any other dimensions impacted students' trust/mistrust toward simulations. To this purpose, we qualitatively analysed students' explicit responses to the questions of the fifth section of the protocol, identifying the factors they mentioned speaking of their perception of trust. After this step, we triangulated the previous analysis by looking back at the other parts of the interview searching for markers testifying that the factors we identified were not occasional but there were utterances of them in the previous students' discourses. Finally, we looked for possible relationships between their trust/mistrust, the typology of simulation under discussion and the kind of explanations they formulated.

5. Data analysis and results

5.1. Students' explanations about simulations of complex systems

The first part of the analysis showed that the identification of the components of a mechanism in each simulation was not sufficient to favour actual explanations. As an example, we report the case of Elizabeth's reasoning about the simulation of Schelling's model. When asked to describe what she sees in the simulation, she is able to identify elements of the mechanism behind it:

> *It is presented a grid in which a half are squares and a half are triangles. These figures move on the basis of their preference and everyone tries to have a certain percentage of similar people. When the simulation runs, we notice that little tendencies of all the individuals lead to global tendencies. (Elizabeth)*

Indeed, she recognises the target phenomenon (the *global tendency* to segregate), the entities (*squares* and *triangles*), the setup conditions (*a grid in which a half are squares and a half are triangles*), the activities of the entities (their ability to *move on the basis of their preference* to fulfil the conditions of having *a certain percentage of similar people* as neighbours). Despite this, when requested to explain the phenomenon of segregation, she just explicates it, describing what she sees at the end of the space-time evolution of the system:

> *At the end of the run, we notice that the figures are not mixed: they start from a mixed situation and at the end they are divided. This is the phenomenon of segregation. (Elizabeth)*

We categorize this one as an explication since the student just *notices* a behaviour of the system, without investigating the causes behind it. As a confirmation of this interpretation, when asked if this simulation could provide any explanation about why the phenomenon unfolded the way it did, Elizabeth answered that:

> *the simulations just say how, not why. (Elizabeth)*

Similar explications of complex phenomena can be found also in other interviews.
In only few cases the students appeared to be able to go beyond mere explications, toward proper explanations: this is the case of Anthony when reasoning about the Lotka-Volterra model and of Lily about Schelling's model. Anthony starts from the observation of the graph, rephrased with an explication (he uses the verb *notice*, as Elizabeth did before):

> *From the graph we notice that prey increase exponentially, while a little increasing in the number of predators causes a dramatic decreasing of prey. (Anthony)*

Going forward with the interview, he gives an explanation about the emergent periodic phenomenon:

> *There is a maximum of predators and a corresponding maximum of prey, but soon it falls down till zero. Here, naturally, the predators have to follow this tendency: since there are no more prey, they will die, and it will restart from a minimum of both. (Anthony)*

We categorize this explanation as covering-law, since Anthony ascribes the behaviour of the populations to a natural law expressed as a regularity, a t*endency* they *have to follow*: it can be noticed that the law that, according to this student, covers the phenomenon is not expressed in a symbolic form but this is not necessary in covering-law explanations, where "false-laws" and law-like statements, like the one expressed by him, are permitted (Cartwright, 1997). Another covering-law explanation is that formulated by Lily about Schelling's model:

> *Triangles and squares are forced to move in order to satisfy the rule of having one third of their neighbours similar to them; the lower is the tolerance, the more the individuals will be divided and grouped. (Lily)*

The covering-law character of this explanation is given by the fact that Lily ascribes the cause of movement leading to segregation to the need of *satisfying the rule* of having a certain percentage of similar neighbours. This explanation is partial and does not really explain the final segregated state reached by the system, but just the local movement of the agents; anyway, considering it as an explanation we are able to identify its limits and its explanatory power, which, in the case of self-organizing systems, is weak.

5.2. Students' trust about simulations

Analysing the transcripts of the two interviews, we noticed differences in the approaches of students with different epistemological backgrounds. Elizabeth and Anthony, who had been taught science also from an epistemological perspective, seemed more aware, consistent, and able to critically evaluate the use of simulations. For instance, Anthony reflects about Schelling's simulation as follows:

We don't have to take squares and triangles literally but like a social experiment which – through a totally mathematical, rigorous, and deterministic simulation – becomes a possible model to understand how certain behavioural tendencies develop. (Anthony)

Then, he expresses a robust confidence in simulations, according to a principle of similarity between the objects and processes represented in the simulations and the reality, but he remarks a need to interpret the results in particular cases, when there are constraints in the target dominium which are absent in the source one:

In general, I trust simulations because they are models similar to reality, but they have to be interpreted in order to move to the right conclusions. If we think at the real case of 90% preference, we know that there cannot be infinite moves […]: people don't have even the money to move so many times! (Anthony)

On the opposite, Evelyn and Lily, two students with weak awareness of epistemological issues, did not trust simulations. The reason for this lack of confidence is expressed by Lily when she reasons about Schelling's simulation:

I don't trust it because we are talking about a phenomenon regarding people, so I don't think it is possible to quantify scientifically everyone's tolerance. If I had a city with 120 individuals and I used a simulation like this, I wouldn't be sure to find the real result! (Lily)

For her, the scientific character of the simulation could be recognized only if it provided predictions and explanations for the behaviour of each individual agent: since it is not possible, the simulation cannot be trustworthy. We suppose that her attitude finds its roots in her naïve belief about the meaning of model in general, that is considered reliable and well-posed to provide explanations if and only if it is substantially a copy of the real target system.
Such a naïve approach was accompanied also by other statements about the factors that the students considered important to make a simulation reliable, e.g. i.e. a simulation with a higher number of parameters, or one that takes as inputs "real data" could have been considered more accurate. We think that these criteria expressed by students deserve to be better investigated in further studies.

6. Discussion of the results

The data analysis allowed us to point out some preliminary findings that we can summarize in two main points that we are going to discuss. The first finding confirms the research results about the novices' difficulties in interpreting complex phenomena. Even if the students correctly identify the main components of the mechanism behind the simulations, most of them are not capable of formulating proper explanations about the complex simulated phenomena. In most cases the simulated phenomena are just explicated. We also noticed that in the cases of explanation, simulations of complex systems activate only covering-law, teleological or intention-based explanations, while there is not any trace of mechanistic explanations. Indeed, the students use a normative lexicon to describe individual agents that, via the rules they follow, are forced to lead to a higher-level configuration of the system. This finding is coherent with the previously cited literature in science education highlighting the novices' difficulties in renouncing the deterministic-centralized mindset typical of classical science.

A second relevant finding is that students' weak awareness of epistemological issues was linked to a lack of trust and confidence about simulations. The analysis of students' discourses showed that this sceptical attitude could be ascribed to naïve epistemological conceptions about, for example, the role of models in science and their predictive power. On the contrary, the students who had been taught science also from an epistemological perspective expressed more confidence toward the simulations. Their discourses revealed deeper reflections about the meaning of the simulations as well as critical and more aware evaluations about their possible uses and applications.

Alongside these two findings, this pilot study also revealed some methodological weaknesses. Even if the paired interviews allowed us to observe the rich and frequent interactions among students, they did not consent to obtain all the answers to the questions of the protocol for each simulation proposed. Indeed, in many cases one of the two students dominated, not giving to the other equal opportunities to express herself/himself, especially in case of disagreement. Since this result is consistent with the literature about paired interviews (Morris, 2001), we plan to revise the methodology of data collection for further studies, in order to be able to draft comparisons between the approach to simulations of classical vs complex systems for each student involved. In this way, we could investigate whether the classicality or complexity of the model behind the simulation is one of the factors influencing students' trust.

7. Conclusions

In this study we dealt with the issue of the scientific skill gap, investigating specifically the factors affecting high school students' trust in computer simulations as scientific tools that help in formulating possible explanations of phenomena.

We noticed that the students rarely appeared to be able to elaborate explanations by themselves using simulations. Furthermore, the students' criteria to establish their level of trust in simulations were scarcely based on scientifically significant arguments but in the case of the two students explicitly taught in epistemology of science within the ordinary science classes. We argue that this finding deserves to be furtherly investigated: that is, students at the end of their mandatory school curriculum, after having studied science for many years in the highest-level schools (*lyceums*), are not able to critically interpret the epistemological and methodological value of a scientific simulation.

For what concern the specific difficulties concerning complex systems and the lack of interdependence between mechanism descriptions and causal explanations, we hypothesize that the difficulties in generating mechanistic explanations about complex phenomena are linked to the difficulties in constructing autonomously a "mid-level" between the agent-based description and the aggregate one. This mid-level, that the literature in science education has claimed to be particularly relevant in the process of making-sense of complex systems (Levy & Wilensky, 2008), could be important also in formulating mechanistic explanations that have to connect individual behaviours to global properties, through intermediate involving little groups of agents.

We plan to develop further studies in which problematize the epistemology of simulations and include the features the students said to make a simulation more reliable, in order to investigate if and how these sceptical attitudes persist or give birth to more articulated reflections.

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Chapter 3 -
Recognizing simulations as the third pillar of research[6]

In an increasingly complex world, the science of complex systems is well-positioned to provide epistemological lenses and methodological tools to analyze the reality. Among the tools developed, computer simulations have a crucial role, but the ways in which they are conceptualized by graduate and undergraduate students have not been extensively explored. Framed within wider research about the educational role of simulations of complex systems, the goal of this work is to provide insights into the understanding about simulations of university Physics and Mathematics students. For this purpose, a study has been designed with a group of bachelor and master students within a course of Physics Teaching. The object of this chapter is to present the results of the data analysis of the preliminary questionnaires, where 27 students were asked to express their ideas about simulations. The bottom-up process of qualitative analysis has allowed to point out, and organize in categories, different ways in which simulations are conceptualized by the students, in terms of: i) scope for which simulations are used, ii) their relationship with experiments and models, and iii) the examples of simulations they refer to.

1. Introduction

From the 50s, the use of computer simulations in the sciences has become more and more widespread. Their development is core part of the research in physics, climate science, ecology, sociology, and in many other disciplines. There are even specific disciplines, like the science of complex systems, “whose very existence has emerged alongside the development of the computational models they study” (Winsberg, 2019). Their role in the scientific enterprise has become so important that there are authors who have defined them the “third pillar of science”, alongside with theories and laboratory experiments (Parisi, 2001; PITAC, 2005). This revolution

[6] The contents of this chapter are the object of a paper entitled “Physics and Mathematics university students’ ideas about computer simulations” (Barelli, 2021) which is based in turn on the homonymous extended abstract accepted for an oral presentation at the GIREP 2019 Conference (Barelli, 2019a). The study was also object of a communication at the SIF 2019 Congress (Barelli, 2019b).

represents nowadays a routine for the academic research but the epistemological debates about computer simulations are intense. The main challenge consists in characterize the peculiarities of simulations and, in particular, if and how they constitute a novelty with respect to models and to computational sciences in general (Humphreys, 2009; Frigg & Reiss, 2009).

In spite of the increasing relevance of the topic, simulations are rarely addressed at school and university levels from an epistemological and methodological point of view. Here we need to clarify that two macro-meanings are associated to the term "simulation". On one side, we have *scientific* simulations, the third pillar of research, whose definition we will discuss in the next section and that are the object of this chapter. On the other, we have *educational* simulations, "interacting learning environments in which a model simulates characteristics of a system depending on actions made by the student" (Kirschner & Huisman, 1998). While the formers aim to reach a better expert understanding of a phenomenon basing on theories, the latter aim to favour a better understanding of the model and theoretical principles at its basis (Greca, Seoane & Arriassecq, 2014). In high schools, in recent years the use of educational simulations has increased (Smetana & Bell, 2012; Rutten, van der Veen & van Joolingen, 2015), but they are still used almost exclusively as a teaching aide for showing physical, biological, or chemical phenomena in different ways than traditional laboratory experiences (Jimoyiannis & Komis, 2001). At the university level, scientific simulations are not part of most undergraduate scientific curricula (Gould & Tobochnik, 2001). In the Physics bachelor curricula, the only type of simulation introduced in mandatory laboratory courses is the Monte Carlo method - even if there is a debate about its nature of simulation or just of computation (Grüne-Yanoff & Weirich, 2010). Other types of simulations, such as agent-based or equation-based simulations of complex systems, are only rarely mentioned. More generally, these ways of introducing simulations often hinder to value the cultural relevance of computer simulations and the epistemological challenges they present to the methods of contemporary science (Gould & Tobochnik, 2001).

Framed within wider research about the educational potential of simulations of complex systems and the differences between experts and novices in facing these tools (Barelli, Branchetti & Ravaioli, 2019; Barelli, Branchetti, Tasquier, Albertazzi & Levrini, 2018; Levrini, Tasquier, Branchetti & Barelli, 2019), this work aims to contribute to characterize the ideas that university Physics and Mathematics students have about computer simulations, which is an unexplored issue by educational research. In this chapter, we present: i) the theoretical framework about scientific simulations from the literature in epistemology of science; ii) the study, with a description of the context in which it was carried out, the data collection tool, the sample of students; iii) the methodology of data analysis; iv) the results of the data analysis, discussed in terms of their contribution to answer the research question and to the research framework.

2. Theoretical framework

In this section we outline the theoretical framework about scientific simulations from the literature in epistemology of science. It is articulated in three sections that discuss: i) some definitions of simulations; ii) the relation of simulations with experiments and models, iii) the main types of simulations.

2.1. The search for a definition of simulation

The philosophical literature on simulations has increased dramatically during the past 40 years and many attempts have been made to provide definitions of what a simulation is (Grüne-Yanoff & Weirich, 2010). In spite of this, the propositions elaborated are not very informative by themselves, but they deserve attention because of the ways in which they consider important epistemological and methodological issues such as the relation of simulations with experiments and models or the scientific uses of simulations. We discuss here three main definitions and the issues they highlight. Humphreys, in 1990, has defined a simulation as:

> *"any computer-implemented method for exploring the properties of mathematical models where analytic methods are not available" (Humphreys, 1990)*

Here, simulations are meant as purely computational tools, used for exploratory aims; simulations for which analytic methods are available are excluded from this definition. In 1996, Hartmann enlarges the categories considered by saying that:

> *"a simulation imitates one process by another process" (Hartmann, 1996)*

Now, simulations are not necessarily computational tools, but they all have an imitational aim; focusing on the processes, the definition excludes simulations that use a model to represent structure (not dynamics) of systems. A third definition is provided again by Humphreys in 2004:

> *"System S provides a core simulation of an object or process B just in case S is a concrete computational device that produces, via a temporal process, solutions to a computational model [...] that correctly represents B, either dynamically or statically" (Humphreys, 2004)*

Here, three layers intersect: R the real system, B the model of object or process, S the simulating system; the simulation aims to solve a model and S is always a temporal process, even if the R is not necessarily dynamic.

2.2. *The relation of simulations with experiments and models*

Given the variety of simulations and of their uses, more than about the search for a univocal definition of simulations there is a vivid debate about characterizing their position with respect to models and experiments, the other two "pillars of science" (Parisi, 2001; PITAC, 2005). Indeed, it is only from the comparison with them that the "novelty" of computer simulations can be discussed and articulated. Sketching a complete framework about the different epistemological positions about these topics would be an extensive work and goes beyond the aims of this chapter. Also

discussing the issue of novelty of simulations for the epistemology of science is not the object of this section, but, in this paragraph, we summarize the main issues that will help in the next sections to orient in the methodological choices for the data analysis. Accurate reviews can be found in (Winsberg, 2019; Grüne-Yanoff & Weirich, 2010).
In the experimental sciences, and in physics in particular, simulations often flank traditional laboratory experiments, and it has become somewhat natural to see them as computational versions of experiments (Kaufmann & Smarr, 1993). This idea holds in particular when a simulation study is designed to learn what happens to a system as a result of various possible interventions on its parameters. In this sense, the interaction with the surface of the simulation recalls the experimental process. Another focal question in the relation with experiments is whether the data obtained from simulation can count as measurements. About this, Norton and Suppe (2001) claim that if a simulation is valid, that is formal relations hold between a base model, the modelled physical system itself and the computer running the algorithm,

> *"a simulation can be used as an instrument for probing or detecting real world phenomena. Empirical data about real phenomena are produced under conditions of experimental control" (Norton & Suppe, 2001)*

Despite these common traits, there are views for which simulations differ from experiments. The first argument points to the different similarity relation that experiments, and simulations have with their targets: in a simulation, rather than experimenting with the object of interest, one controls parameters of a model (Gilbert & Troitzsch, 1999). Connected to this, there is a difference in the degree of materiality and authors argue that this makes experiments epistemically privileged compared with simulations, since simulations have only a formal relation to their targets (Morgan, 2003). Another argument regards the sources of justification. For a simulation, justification rests on our trust in the background model, while, for experiments, justification relies on the fact that experimental object and target are of the same kind.
Simulations are often related also to models. For example, it is said that simulations are "based on" models or that there is a model "underlying" the simulation. But simulations and models differ mainly in their temporal expansion and in their epistemic opacity. About the first point, the model underlying a simulation is often referred as a static one (Grüne-Yanoff & Weirich, 2010), while the time evolution is intrinsic to the dynamical modelling of the simulation. The second difference lies in the methods by which models can be solved: indeed, simulations are used in particular when an analytic solution to the "underlying" model is not available. This is for example the case with complex systems (Cilliers, 1998). In this case, the simulation executes sequences of calculations obtaining a list of numbers which can be interpreted as the numerical solution of the model. The specificity of this kind of calculations is that, despite the code can usually be written in procedural-imperative, human-readable languages, the way in which the simulation "solves" the model deriving the results is in general outside of the reach of human agents. Humphreys has named this behaviour as the "epistemic opacity" of computer simulations (Humphreys, 2009), which is a feature absent in standard analytically solvable models.

2.3. Types of computational simulations

Two main types of computational simulations can be distinguished: the equation-based and agent-based ones. Both types of simulations are used for different sorts of purposes such as prediction and explanation. In the case of equation-based simulations, the evolution of a target system is described by differential equations. Once they are numerically solved, they allow to determine the future state of the system starting from the present state. In the equations, variables related to the macroscopic system appear. In agent-based simulations, the dynamics of the target system is generated making the individual agents evolve according to behavioural rules. There is no description of the macroscopic properties of the system. These instead "emerge" as a result of the execution of the simulation.
Another large class of computer simulation is that of the Monte Carlo methods. They are algorithms that use randomness to calculate the properties of a mathematical model. The Monte Carlo approach does not have imitative purposes since the probabilistic analogy does not serve as a representation of the deterministic system (Grüne-Yanoff & Weirich, 2010). That is why Monte Carlo simulation can be considered simulations but, in general, not simulations *of the systems* they refer to (Winsberg, 2019). There are exceptions, in the cases in which Monte Carlo techniques are used to solve stochastic dynamical equations that refer to a physical system: in this case the probabilistic analogy is itself a representation of the system it simulates (Beisbart & Norton, 2012).

3. The study

The goal of this work is to provide insights into the understanding about simulations of a group of university Physics and Mathematics students, attending a course of Physics Teaching. In particular, we are interested in pointing out to which extent the definitions they construct of simulations reflect the debates in epistemology of science illustrated in the previous section. The study we present in this chapter provides a qualitative survey of university students' ways to conceptualize scientific simulations, in absence of a specific teaching focused on methodological and epistemological aspects.

3.1. Research questions

The overarching question guiding this work is: *In absence of a systematic intervention, what level and kind of knowledge do university Physics and Mathematics students display about computer simulations?* Because of the general character of this question that refers only to a generic "knowledge about simulations", we needed more specific research questions (RQs) to orient the design of the study and its analysis. They are:

RQ1. What are students' ideas about the scope of simulations?

RQ2. What are students' epistemological ideas about the relationship of simulations with respect to models and experiments?

RQ3. What are the simulations that students take as reference to provide their answers?

To answer the RQs, the data analysed for this chapter have been collected through a questionnaire submitted to the participants in a course of Physics Teaching, before a series of instructional activities. Because of this, even if it is not the specific focus of this chapter, we will provide an overview of the whole study and the activities carried out. In the following paragraphs we present i) the context in which the study was carried out; ii) the data collection tool, iii) the sample of students and iv) the methodology of data analysis.

3.2. Context

The study was carried out in December 2018 within a course of "Physics Teaching" at the Department of Physics and Astronomy of the University of Bologna. The course is traditionally mainly attended by bachelor Physics students, who can choose this course from the "optional list" of the curriculum. In recent years also master students in Physics, Physics Education and Mathematics Education have started to attend it. During the course, fundamental physics issues are addressed (e.g. kinematics, mechanics, optics) and the students are guided to develop, through these disciplinary issues, knowledge and competences typical of the research field of Physics Education. Specific attention is paid to the role of history and epistemology in physics teaching and learning, with a particular focus on the role of models in physics (and in science in general) and on the modelling processes. The course usually runs from October to December and the intervention we describe here came just at the end of it.

3.3. Intervention and data collection

On the whole, the intervention was designed and implemented in three main phases preceded by a preliminary activity. Before the beginning of the intervention, that we will describe briefly at the end of this paragraph, an online questionnaire was submitted to the students of the course. This was the data collection tool for the analysis presented in the next section. The questionnaire consisted in five open-ended and one close-ended questions. They aimed to give insight into students' knowledge on the issues of simulation and complex systems. More specifically, after a section that required information about the university curriculum attended by the students, the questions were formulated as follows:

- *What do you mean with simulation in scientific field? Have you ever heard about it?*
- *For which purposes do you think simulations are used?*
- *In your opinion, is simulating closer to modelling or experimenting? Why?*
- *During you school and university career, in which areas have you encountered simulations? Which kind? For which purposes?*
- *During your school and university career, have you ever studied complex systems? (Y/N)*
- *How would you define a complex system?*

After this preliminary phase, the study was articulated in three parts. The first consisted in a lecture of an hour and a half about the specificities of computer simulations to analyse complex systems. Not only examples within physics but also complex systems in other fields were introduced (e.g.

social sciences, economic, climatology). Indeed, the aim of the lecture was to show how wide the research in complexity is and how powerful are its conceptual tools, to the point that they provide descriptions and explanations of very different phenomena. One week after the lecture, a focus group activity was carried out; the task assigned was to analyse two simulations of complex systems (about Schelling's racial segregation and Lotka-Volterra predator-prey interaction) and answer some questions related to explanation and trust. The intervention ended with a dialogic lecture of an hour in which the results of a pilot study with secondary school students (Barelli, Branchetti & Ravaioli, 2019) were presented, in order to trigger meta-reflections about the use of simulations in the classrooms.

3.4. Sample

The total number of students who participated at least in one phase of the study is 36, 20 males and 16 females. The presence of the students was not constant throughout the phases of the study. In particular, 27 students participated in the preliminary activity filling the online questionnaire, while 29 of them took part in the focus groups discussion. In the following, we will focus on the participants in the preliminary activity because the questionnaires filled by them were the data considered and analysed for this chapter. From here, when we refer to "the students" we mean the 27 participants in the preliminary activity. The students were distributed across university curricula as represented in figure 1. The majority of them were undergraduate students in Physics, at their third year in the bachelor course in Physics. The others were graduate students enrolled in master courses in Physics (Particle Physics, Materials Physics and Earth System Physics), Physics Education and Mathematics Education.

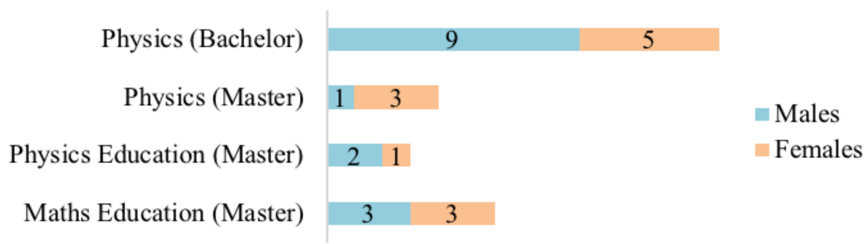

Figure 1. Distribution of the participants in the study across curricula.

4. Methodology of data analysis

The analysis has been carried out to answer the aforementioned RQs. To address them, the 27 responses to the preliminary questionnaires described in 3.2 have been considered, in particular to the first four questions of the protocol. The data analysis was carried out with a qualitative methodology, through a theoretically oriented iterative process of analysis and interpretation, where the hypotheses formulation was progressively refined through an enlargement of the empirical base, until theoretical saturation was reached (Denzin & Lincoln, 2005). Due to the exploratory nature of this research, the analysis was mainly conducted with a bottom-up strategy, that is the categories were obtained, and the markers clarified, starting from students' answers. Nevertheless, once extracted from the data, the categories were organized also on the basis of the studies in epistemology of simulations, mainly referring to the uses of simulations for scientific inquiries and the distinction among models, experiments and simulations (Gould & Tobochnik, 2001). The data were analysed also to look at possible differences between Physics and Mathematics students and between bachelor and master students. Triangulation among researchers has been carried out to ensure validity and reliability of the analysis. More specific methodological choices for data analysis will be made explicit and detailed in the next section.

5. Data analysis and results

Following the three RQs, the analysis has been articulated to recognized in students' answers three main levels. These are: i) the level of *scope* of simulations; ii) the level of *epistemological ideas* about simulations; iii) the level of types of simulations used as *references* to provide the answers.

5.1 Students' ideas about the scopes of simulations

The first item of the questionnaire required to attempt a definition of simulation in science. Nevertheless, most students give their definitions in terms of their scope. Indeed, they do not elaborate definitions of simulation itself, but rather describe "what a simulation is supposed to be designed/realized for".

Among the scopes of simulations, we have identified four macro-categories. The first is related to the aim of simulation of *recreating* "something" (e.g. physics phenomena, models, processes, situations) in a virtual environment. The second refers to the aim of simulation of *displaying the evolution* of "something" (e.g. models, systems) starting from facts (e.g. initial conditions imposed in the simulation, data obtained from laboratory experiments, knowledge of the past evolution). Even if the first aim – recreating – and the second one – displaying the evolution – could be considered strictly related, we prefer to distinguish them because the second meaning involves a dynamical aspect which is absent in the first one. The third macro-category regards the use of simulation for *obtaining predictions*. The last one refers to the scope of *testing* "something" (e.g. hypotheses, models, theories, algorithms, alternative scenarios) against facts (e.g. real-world data, data to be obtained from laboratory experiments). We detail these categories in table 1 where we provide operational descriptions and flank each of them by an example of students' sentence. To ensure students' anonymity, their names have been omitted and only the referral to gender has been kept.

The frequency of the four macro-categories in students' answers is reported in figure 2.a while in figure 2.b a more detailed picture of the different categories is provided. A students' answer could represent more than one category, so the totals can add up more than 27. In this graph and in the following ones, we do not distinguish between bachelor and master students because no significant differences were found in the recurrence of answers; this is probably due to the fact that the course is attended by students at their last year of bachelor and by others at their first semester of master.

Table 1. Operational description of the markers for the categories of ideas about the scopes of simulations.

[Rec] Recreating something in a virtual environment	
"Technique applied in the study of physical phenomena that are difficult to reproduce in the laboratory; a mathematical model and calculation tools are then used to *reproduce the phenomenon in a "virtual" way*" F23	
[Evo] Displaying the evolution of something starting from facts	
[Evo1] Displaying the evolution of a model	"Simulation is for studying the *evolution of a model* or a theory" M33
[Evo2] Displaying the evolution of a system	"The simulation represents the *operation of the system over time*" F16
[Evo3] Starting from initial conditions	"It is a test in which you recreate the *initial conditions from which* a certain phenomenon originates, and you study it" M24
[Evo4] Starting from experimental data	"A simulation shows the effects of a model or a theory *starting from the experimental data* collected initially" M31
[Evo3] Starting from past known evolution	"A simulation is something *based on* the study of the *past evolution* or the *known behaviour of a certain phenomenon*" F25
[Pre] Obtaining predictions	
"Simulations are used to predict the results of a certain phenomenon" M36	
[Test] Testing something against facts	
[Test1] Testing algorithms	"Data acquisitions can be simulated to test analysis algorithms" M29
[Test2] Testing theories, hypotheses or models	"The simulations are used for the corroboration of a theory" M5
[Test3] Testing alternative realities	"Having the possibility to modify the conditions and methods of action of the system, we can *foresee the alternative ways of functioning*" F16
[Test4] Against real-world data	"A first purpose of the simulations is to verify whether a hypothesis is *compatible with the observed physical reality*" M32
[Test5] Against the data to be obtained from laboratory experiments	"They are used to obtain the predictions of the models [Pre] and then to *compare the simulation data with those acquired experimentally*. From this comparison, the "truth" of the model is evaluated [Test2]" M19

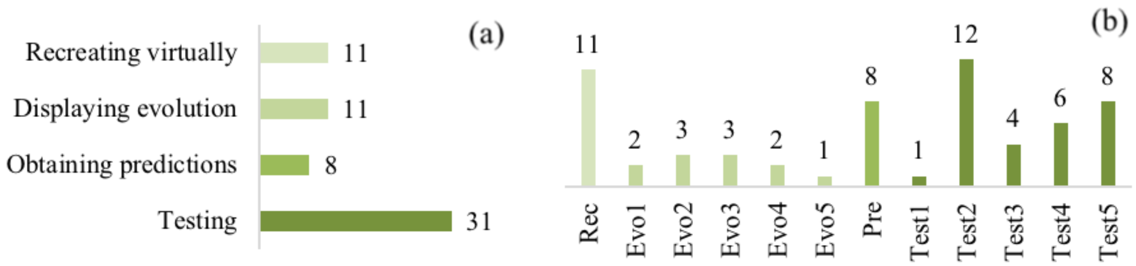

Figure 2. Frequency of the macro-categories (a) and detailed categories (b) of ideas about the scope of simulations in students' answers.

5.2. Students’ epistemological ideas about simulations

Going beyond the level of the scope for which simulations are designed and used, the second level we address is that of the students’ epistemological ideas about simulations. To perform this analysis, we considered in particular the responses to the third item of the questionnaire (*In your opinion, is simulating closer to modelling or experimenting? Why?*). Also because of the way in which the question was formulated, three macro-categories of ideas emerged: simulations as experimental tools, simulations as modelling tools and simulations as “in-between” tools. Even if in their answers to this question the students positioned themselves in one of these macro-categories, the richness of the reasonings they performed throughout the whole questionnaire allowed a refinement of the analysis and an articulation of the macro-categories in more specific ones. We detail these categories in table 2 through operational descriptions and flank each of them by an example of students’ sentences.

Table 2. Operational description of the markers for the categories of epistemological ideas about simulations.

<table>
<tr><th colspan="2">[Exp] Experimental tool</th></tr>
<tr><td colspan="2">“I believe that simulating is closer to experimenting. In a simulation, starting from a significant model (which is already built, and does not derive from the simulation itself), we obtain a result that tends to be what we could measure (therefore, experiment) in reality” M32</td></tr>
<tr><td>[Exp1] Experimental tool for data acquisition</td><td>“Simulation is a process to obtain "fictitious" data produced by following various physical/mathematical models which therefore show how a sample of "real" data would be if certain theoretical criteria and experimental criteria were met” F10</td></tr>
<tr><td>[Exp2] Experimental tool for rare events or difficult to experiment with traditional methods</td><td>“The simulations are often used instead of experiments, when they are of difficult realization” M22</td></tr>
<tr><th colspan="2">[Mod] Modelling tool</th></tr>
<tr><td colspan="2">“I think it is closer to modelling because I visualize the idea of experimenting as "from the practical to the theoretical" while modelling and simulating "from the theoretical to the practical"” M5</td></tr>
<tr><td>[Mod1] Model of an experiment in a virtual laboratory</td><td>“A simulation is the model, the reproduction of an experiment, virtually executed by a calculator” M30</td></tr>
<tr><td>[Mod2] Model in which non relevant aspects or elements are removed</td><td>“It is closer to modelling because of a phenomenon we take into account only the characteristics we consider necessary for the purposes of our research” M36</td></tr>
<tr><th colspan="2">[Exp-Mod] In-between tool</th></tr>
<tr><td colspan="2">“The simulation shares, in the process of scientific discovery, the role of experimentation and, in this sense, it resembles it. At the same time, however, a simulation contains the model and evolves according to its rules, which instead cannot be said of the experiment, which takes place following the laws of the real system, which are the object of the modelling attempt” M29
“To simulate a phenomenon it is necessary to develop a mathematical model that describes it completely; on the other hand, a simulation is a sort of "virtual experiment", so one must then be able to apply the model and interpret the information provided by the simulation, as is done in experimental physics” F23
“I see simulating as close both to modelling, since a numerical-abstract procedure (algorithms) is carried out, and to experimentation, since it is as if a "parallel" experiment was performed beside the actual and "physical" experiment (in the sense of concrete)” F13</td></tr>
</table>

The frequency of the three macro-categories in students' answers is reported in figure 3.a while in figure 3.b a more detailed picture of the different categories is provided.

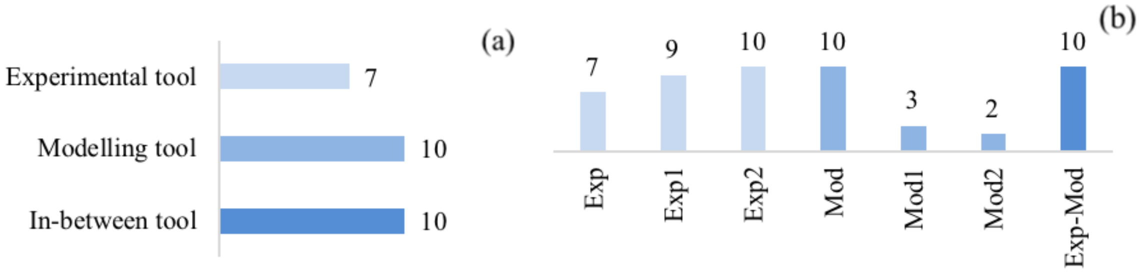

Figure 3. Frequency of the macro-categories (a) and detailed categories (b) of students' epistemological ideas about simulations in students' answers.

5.3. Students' references and known examples about simulations

The third and last level regards the types of simulations encountered by the students in their school or academic curricula and used as references to provide their answers to the questionnaire. The majority of the students referred as the only type of known simulation the Monte Carlo method used in particle physics to generate data according to probability distributions. Indeed, a module within the course of Physics Laboratory, in the second year of Physics bachelor, includes the basics of the Monte Carlo computation. Few students referred to examples of simulations of complex systems and agent-based simulations in particular. Others cite a wide variety of simulations, both material and computational: for example, electric circuit simulators, flight simulators, simulations for anti-seismic materials. In figure 4, we report the frequency of these references in students' questionnaires. In our study, only Mathematics' students (5 out of the 6) are included in the "no references" category.

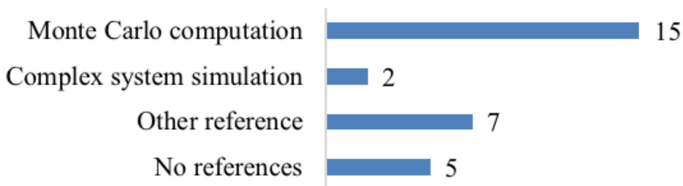

Figure 4. Frequency of the students' references and known examples about simulation.

6. Discussion of the results

The qualitative data analysis has allowed us to point out categories of ways in which university physics and mathematics students interpret computer simulations. In this section, we resume the main results and discuss them in the light of the theoretical framework.

The first result regards students' ideas about the scope of simulations. The recurrences in students' answers have been organized in categories which relate to four different purposes of simulations: recreating something in a virtual environment, displaying the evolution of a model, obtaining predictions and testing. The first two purposes recall Hartmann's definition ("a simulation imitates one process by another process") (Hartmann, 1996) where imitation is related to recreation, and the existence of processes is reflected by the role of displaying the evolution – rather than the structure – of a system. In terms of macro-category, the most represented is that about testing, and in particular testing models. This reflects the idea of simulation as a tool to verify a model, where the computational support allows to run a model from initial conditions, obtain predictions and then compare them against real-world data or data obtained from laboratory experiments. Another widely represented macro-category is the idea that a simulation aims to recreate phenomena or behaviours in a virtual environment. Among the main scopes of simulations, no students mentioned their role for providing explanation of phenomena, which is instead one of the main issues when agent-based simulations are considered (Grüne-Yanoff & Weirich, 2010). The lack of this category can be ascribed to the lack of experience that students have with this type of simulations. Indeed, most of them had as only reference for computer simulations the Monte Carlo method.

The second important result consists in having mapped students' ideas about the epistemological and methodological position of computer simulations with respect to models and experiments. This mapping has been done initially according to macro-categories – simulations as experimental, modelling or in-between tools – then detailed in sub-categories that highlight specific aspects of the experimental or modelling practices that students recognized in simulations. When the students were required to answer if simulating was closer to experimenting or modelling, they positioned themselves in one of the three categories in almost equal numbers. The analysis has revealed that in the experimental tool category there are only Physics students, while all the Mathematics students involved in the study, except one, are part of the modelling tool category. When asked to clarify why they selected this or that category, students' reasonings become rich because different argumentations interact, coming both from experimental and modelling practices. About this, the responses of students who identified simulations as intermediate tools between models and experiments deserve particular discussion. In table 2 we have reported for this category three sentences from three different students. They are Physics students, and their sentences were selected because their argumentations are different and allow to underline different aspects. One student (M29) says that simulation "resembles" an experiment and has its role in the scientific enterprise, but at the same time a model "is contained" in the simulation and this model includes explicit rules and laws that cannot be recognized in the world object of laboratory experiments. The second student (F23) recognizes "the need" of a mathematical model behind the simulation because, on the basis of this model, interpretations can be formulated when the virtual experiment is carried out. Another student (F13) sees the modelling aspects in the "abstractness" of the algorithm while the experimental ones are recognized in the conduction of a virtual experiment that goes in parallel with the "concreteness" of laboratory experiments. These three sentences partially reflect the plurality of debates (formalism vs resemblance, necessity of mathematics vs need of interpretation, abstract vs concrete) that epistemology faces when dealing with computer

simulations. In particular, they re-focus the attention on the importance of making explicit their own views and conceptualizations of models and experiments when reasoning about simulations and their role within the scientific enterprise.
The last comment regards the “great absentee”. Even if it is a focal issue and a prominent object of discussion in the epistemology of sciences as well as in the communities of research about simulations of complex systems, no students have mentioned anything related to the opacity of computer simulations. We can ascribe this to the fact that most students had not really encountered simulations except for Monte Carlo ones in which the opacity does not emerge as an important element. However, we claim that an introduction of this crucial epistemological issue, together with examples of specific simulations, would be fundamental to allow productive reflections on the emerging type of understanding and trust on this kind of methods.

7. Conclusions

Nowadays computer simulations have become an important part of the scientific research and practice alongside with theories and laboratory experiments. In physics, applications of simulations are widespread and different types are used: from the Monte Carlo methods to agent- and equation-based simulations. The impact of computer simulations has gone far beyond the scientific community: indeed, they are at the methodological core of studies on issues like climate change or urban planning, on which policymakers and citizens have to make decisions. To correctly interpret them as scientific instruments requires specific competences that nowadays are at the basis of a responsible citizenship (Greca, Seoane & Arriassecq, 2014). However, scientific simulations are rarely systematically addressed at school and university levels. In particular, in the undergraduate curricula in Physics, simulations are often presented as computational tools through the Monte Carlo methods but instruction about agent- and equation-based simulations is not mandatory. This work aimed to investigate the ideas about computer simulations of a group of Physics and Mathematics university students. It has shown that, even if many epistemological stances can be recognized in students’ words, severe gaps persist, and they can be ascribed to the absence of a systematic teaching in university curricula about simulations and the challenge they pose to scientific research. We claim that including in curricula specific moments of conceptual, methodological and epistemological reflection about simulations would contribute to foster the development of competences to move across different modes and tools of science – theories, models, simulations, experiments, computations – without losing the perception of their specificities. Further studies will show how the picture obtained with this chapter of the ways in which university students conceptualize simulations led to the development of learning modules in which simulations are addressed not only as powerful tools for calculus, but as a novel form of scientific production.

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Remarks from Part 1

In this first part of the dissertation, we have reported three preliminary studies conducted during the first two years of the Ph.D. program. They have an exploratory and empirical nature since they were designed to enter the topic of simulations of complex systems by trying to understand the difficulties that novices encounter when they are exposed to them and the ways they describe them. We name this part as the *pars destruens* of the dissertation because allows to point out the critical points to address in the following chapters.

The first chapter reported a study with adult citizens and examined the potential of complex systems, introduced – among other tools – with computational simulations, to trigger the development of citizenship skills.

The study presented in the second chapter involved high school students and concerned the explanations that students formulated on emergent phenomena typical of complex systems relying on the correspondent simulations.

A further target group was involved in the study reported in the third chapter in which we discuss the ways in which university students of Physics and Mathematics conceptualize simulations as the "third pillar" of scientific research.

For the story told in this dissertation, these studies were important since allowed us to:

- explore the research literature on topics related to simulations of complex systems such as their explanatory power and the philosophical perspectives on them;
- recognize the potential of complex systems and simulations to foster citizenship competences to support decision-making processes;
- detect emotional barriers that in novices can hinder the recognition of simulations as authentic scientific tools;
- identify the differences between simulations created for educational purposes and those developed for scientific investigation, both from a conceptual point of view, and from an empirical perspective for the reactions they can trigger in novices;
- point out the need of constructing activities to guiding the students to go beyond the surface of simulations and recognize that they are based on physical, mathematical, and computational models;
- understand that also for Physics and Mathematics students many crucial epistemological features of computational simulations, like their epistemic opacity and exploratory aims, are not part of the ways in which they describe and conceptualize these tools.

Part 2

Part 2 is the core part of the dissertation, its epistemological heart. Here, we report the studies conducted during the second and third year of the Ph.D. program to investigate the epistemological revolution of complexity through machine learning and computational simulations. Vice versa, epistemological categories typical of complexity becomes in this second part of the dissertation the way to recognize in artificial neural networks and in the susceptible-infectious-recovered model two complex models that reflect in an "object" the cultural revolution brought by the complexity science. We refer to this second part as the *pars construens* of the dissertation since it sets the basis, on a multiplicity of levels, for the design and implementation of the teaching proposals that will be presented in the third part.

Chapter 4 - The paradigm shift of machine learning and the revolution of complexity: the case study of neural networks[7]

Big data and new data analytics, such as machine learning techniques, are ground-breaking innovations that are not only changing the ways in which research is conducted but are also challenging epistemologists to investigate the nature of this new science and its distance to traditional statistics and computer science. Goal of the study is to contribute to characterizing the epistemological novelty of machine learning with respect to other approaches to artificial intelligence: the imperative-procedural and the logical-declarative. We address this issue from the perspective of educational research in STEM (Science, Technology, Engineering and Mathematics), guided by the question: which discourses can be introduced to upper secondary-school students to make them aware of the epistemological and cultural revolution introduced by machine learning?
In the chapter, we will present an educational activity about the topic of artificial neural networks, designed and carried out within a teaching-learning module on artificial intelligence. The analysis of the activity will be guided by the hypothesis that the machine learning revolution shares some epistemological traits with that introduced by the science of complexity: both imply and require a shift from classical determinism to probability, and challenge the classical definition of explanation of phenomena, because of the epistemic non-reductionism. Basing on this assumption, the activity discusses the parallelism between neural networks and complex systems, referring to a specific system that the students had encountered since the beginning of the module: the birds' flock. The main similarities identified were the emergence of higher-order properties from local rules of

[7] The contents of this chapter are the elaboration of an extended abstract accepted for an oral presentation at the HAPOC 2019 Conference (Barelli & Levrini, 2019). For the description of the module and the activity, we widely referred to the intellectual outputs of the I SEE Project for the sections to which we directly contributed (I SEE, 2019a; I SEE 2019b). This work was also presented as part of communications held by colleagues on the I SEE module on artificial intelligence at the GIREP 2018 (Levrini, Barelli, Lodi, Ravaioli, Tasquier, Branchetti, Clementi, Fantini & Filippi, 2018), CERME 2019 (Branchetti, Levrini, Barelli, Lodi, Ravaioli, Rigotti, Satanassi & Tasquier, 2019) and ESERA 2019 (Ravaioli, Barelli, Branchetti, Levrini, Lodi & Satanassi, 2019) Conferences.

individual agents, the input-output and local-global circularity, and the presence of non-linearities. We argue how the interpretation of neural networks as complex systems allows to illuminate the epistemological change introduced by machine learning – particularly by the connectionist paradigm – with respect to other approaches to artificial intelligence: the emergence of knowledge from data and the sub-symbolism of the approach.

1. Introduction

In the era of Machine Learning, a radical change has been taking place. Undoubtedly, a change in the impact of science and technology on society: not only the applications of machine learning have reached people's life and behaviour (Rudin & Wagstaff, 2013) but they often generate, especially among the younger generations, strong emotional reactions, from a deep curiosity to fears and negative attitudes (O'Neil, 2016). At the epistemological level, philosophy of computer science has started to investigate the implications of new data-driven approaches and there are authors who have seen in these changes a "paradigm shift" (Hey, Tansley & Tolle, 2009; Kitchin, 2014). The supporters of the paradigm shift claim that a new way of doing science is being created, one in which the modus operandi is purely inductive in nature (Prensky, 2009; Clark, 2013). According to these drastic views the data can speak for themselves since they are free of theory. The critics to the empiricist approach argue that each system, including the machine learning ones, is designed to capture certain kinds of data (Berry, 2011; Leonelli, 2012) hence the results cannot be considered as free from theory, neither can they simply ask from themselves free of human bias (Gould, 1981). Between the extreme positions that characterize the debate, it is very common lately to consider a "data-driven science" (Kitchin, 2014) as a hybrid combination of abductive, inductive, and deductive approaches.
Beyond the epistemological debate about how to define the potential on-going "paradigm shift", this issue is of outstanding importance also for research in science education. On one side, big data and new data analytics such as machine learning techniques are disruptive innovations which are reconfiguring in many instances how research is conducted. On the other, these rapid changes in science practice are rarely accompanied by an educational and cultural reflection on the implications of the unfolding revolution. At school, students are taught according to an idea of science that does not mirror the authenticity of the current *modus operandi* of the expert community. Even if works have been starting in this direction (Marques, Gresse von Wangenheim & Rossa Hauck, 2020), we believe that this knowledge gap deserves to be investigated and that STEM education can give its contribution.
This chapter aims to contribute to characterizing the epistemological novelty of machine learning with respect to traditional approaches to artificial intelligence. We do this on the research basis of the Erasmus+ project I SEE (www.iseeproject.eu) that has developed teaching-learning modules for upper secondary-school students about advanced STEM topics, always valuing the epistemological and cultural revolutions that issues like artificial intelligence, climate change and quantum computers embed. From this perspective, we had to address the following research question:

RQ1. Which discourses can be introduced to upper secondary-school students to make them aware of the paradigm shift induced by machine learning?

In this chapter, we present, as contribution to the research question, an activity about Artificial Neural Networks designed for the I SEE module on artificial intelligence. The analysis of the activity, centred around the interpretation of neural networks as complex systems, will allow us to highlight the epistemological aspects that can contribute to characterize the paradigm shift.

2. The I SEE teaching module on AI as the context of the activity about ANNs

2.1. General structure of the I SEE modules

As a module designed by the I SEE partnership, the module on Artificial Intelligence has a structure articulated in five teaching-learning phases that are graphically represented in Figure 1. They are called: i) encountering the focal issue; ii) engaging with the interaction between science ideas and future; iii) bridge activities; iv) future-oriented activities; v) action competence activities. We provide a short description for each phase, while for a detailed description we refer to the related intellectual output of the I SEE project (I SEE, 2019a).

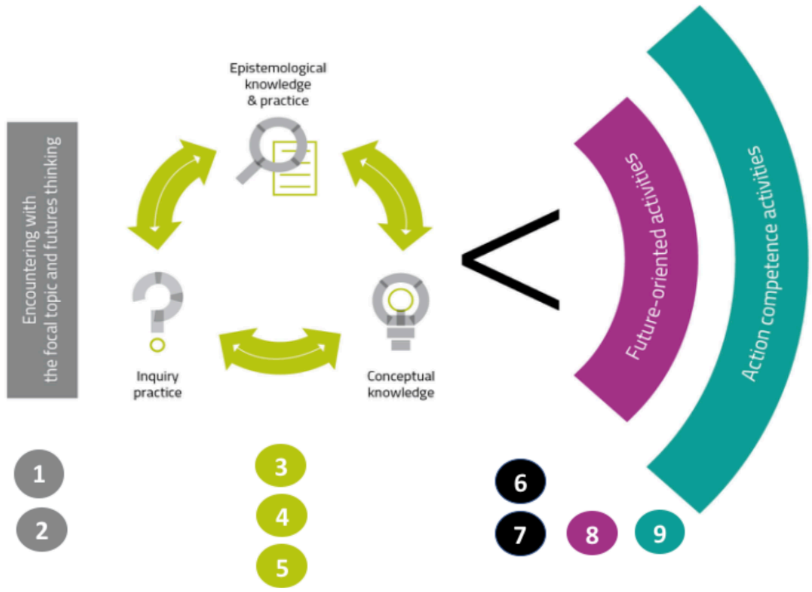

Figure 1. Graphical structure of the I SEE modules and correspondence with the nine activities of the module on AI.

The module begins with students encountering the focal issue of the module (the left, grey section in Figure 1). This phase is aimed at making students develop a preliminary level of awareness of the ways in which conceptual and epistemological scientific knowledge, the specific language, the methodological and the pedagogical approaches will interweave in the module. In this phase, students are also introduced to the connections between STEM and future and some vocabulary to talk about the future as inspired by the literature in futures studies.

The second phase of the module (central, light green section in Figure 1) contains the fundamental elements of the topic that students engage with. The interaction between science ideas and future is represented with a circle that links, in a circular dynamic, the three dimensions of science that are expected to give students a sense of disciplinary authenticity (Kapon, Laherto, Levrini, 2018): conceptual knowledge (focused on the disciplinary contents which are reconstructed (Duit, 2007) in an educational perspective), epistemological knowledge and practice (such as the practices of modelling phenomena, arguing, and explaining), and inquiry practice (such as the skills of posing questions, formulating hypotheses, recognizing modelling as a process of isolating a particular phenomenon, and moving from models to experiments and vice versa).
The third phase (the "less than" symbol in Figure 1) concerns the so-called bridge activities. They are crucial activities in the module since they need to connect scientific, conceptual, and epistemological knowledge and practice (which characterize the first two phases of the module) with the issue of the future (that is specifically addressed with the following activities). In the I SEE modules, this phase was mainly addressed through a work on the concepts of complexity, and the activity which is object of this chapter, about the comparison between ANNs and complex systems, was part of this phase.
During the fourth phase (the pink arc in Figure 1), future-oriented activities are proposed to students. The I SEE approach envisions three types of future-oriented activities that can be developed with the aim of turning knowledge into future-scaffolding skills and competences: a) activities to flesh out the future-oriented structure of scientific discourse, language and concepts; b) activities inspired by future studies or by the working life and societal matters; c) exposure activities to enlarge the imagination about possible future STEM careers.
During the fifth and last teaching-learning phase (the turquoise arc in Figure 1) concerns action competence activities. They aim at triggering awareness of the plurality of perspectives at stake in decision-making processes, and so support students in expanding their ethical consideration as they go forward making intentional decisions and taking deliberate actions. The activities proposed in this phase want to engage the students at a creative and imaginative level.

2.2. The I SEE module on Artificial Intelligence

The module on Artificial Intelligence was articulated in nine activities, following the five-phases structure of Figure 1. We refer to the Ph.D. thesis of Ravaioli (2020) and to the intellectual output of the project (I SEE, 2019b) for a detailed description of the module with its epistemological, conceptual, and societal goals. In the following, we only provide a brief overview of the sequence of activities that will allow to set the context for the description of the activity on neural networks and complex systems.

Phase 1: Encountering the focal issue

Activity 1) Overview lectures on Artificial Intelligence and the perspective of complexity - The activity consists of two overview lectures: the first held by an expert in AI (Prof. Paola Mello, University of Bologna), the second held by an expert in science of complex systems (Prof. Gianni Zanarini, University of Bologna). The lectures aim to introduce conceptual and epistemological knowledge that will be developed and examined in depth in the module. The focus is on: i) the development of AI over the last few years; ii) the different approaches to teaching a machine "to reason" and to solve a problem; iii) the significance of studying a problem from the point of view of complexity. As a follow-up of the two lectures, a teamwork activity is proposed: it consists of two tasks, aimed at reinforcing the concepts of complexity introduced in the overview lectures. The activity is realized through two worksheets and two NetLogo simulations (the flight of a flock of birds and the spread of a virus). The students are given a claim including the main features of complex systems and the first worksheet guides them to identify the words that characterize a complex system. The second worksheet guides the students to explore the two simulations and, for each one, highlight the typical characteristics of the complex systems displayed by the simulations.

Activity 2) Artificial Intelligence everywhere! - The activity sets out to build a map of the state of the art of AI, as an overall picture of where AI can be encountered. Particular emphasis is placed on the different fields of AI applications (archaeology, art, services, scientific research, …), the risks and potentialities of AI applications, and future changes in the job market and STEM careers that the use of AI is going to induce.

Phase 2: Engaging with the interaction between science ideas and future

Activity 3) Introduction to the imperative approach – The first activity of the second phase of the module envisages an introduction to the imperative approach, highlighting the form of reasoning that is employed and, in particular, stressing what an algorithm is (a finite and unambiguous sequence of steps that indicate exactly what actions the machine executes), what does it mean to take a decision within this approach and what it means that the imperative approach is symbolic and top-down. Using the example of the tic-tac-toe implemented in Python, we pointed out that an imperative approach to AI is comprised of data and an algorithm. The actions on the data are executed in a rigid and pre-established order, where an action "cause" the next following the sequence of the algorithm (actions "unroll" in time in a transparent way). In this sense, the imperative paradigm embeds a linear conception of causality and a deterministic idea of prediction.

Activity 4) Introduction to the logical-declarative approach – The activity envisages an introduction to the logical-declarative approach to deductive reasoning by stressing what form of reasoning is employed and, in particular, what is meant by the fact that an explicit knowledge base of the problem is necessary, but it is not necessary to know the actions to be performed, what does it mean to take a decision within this approach, and what does it mean that the logical-declarative approach is symbolic and top-down. Following the same strategy of Activity 3, the example of the tic-tac-toe implemented in ProLog was taken as an example to show that the logical approach to AI is characterized by a deductive reasoning that starts from true premises (the set of facts that constitute the knowledge base) and arrives to the deduction of true conclusions, through the application of declared rules. Differently from the imperative approach, the programmer has to set true facts and correct rules, without entering the detail of the sequence of steps that the machine has to make. Anyway, both the procedural and logical approaches are symbolic and top-down: the strategy is explicitly expressed and coded in the program and needs to be known in advance by the programmer.

Activity 5) Introduction to the machine learning approach - The third activity of the second block consists in an introduction to the machine learning approach to AI by stressing what form of reasoning is employed, and to what extent this differs from that adopted by imperative and logical-declarative approaches. In particular, during the activity is addressed what does it mean for a machine to learn to solve a problem, to make a decision or to perform a task, how an explicit knowledge base of the problem is not necessary, nor is it necessary to know the sequence of actions to be performed, what the role of the programmer is, and what does it mean that the machine learning approach is subsymbolic and bottom-up. To conclude the comparison between the approaches, the implementation of tic-tac-toe with a feed-forward neural network is shown to students. They are guided in the construction of a dataset of matches (making play against each other artificial random and imperative players) on which basis the neural network “learns” how to play. However, instead of learning the most efficient sequence of steps to win, the neural network learns from the examples that are provided in the dataset, and its strategy is probabilistic in nature.

Table 1. Comparison between the three approaches to Artificial Intelligence in terms of the role of the programmer and the epistemological traits.

	Imperative paradigm	Declarative paradigm	Machine learning paradigm
Role of the programmer	To code a non-ambiguous sequence of instructions (organized in procedures) that solve the specific problem for every possible situation	To declare the properties of the desired result through logical statements (facts and rules). The machine will infer the output through an inference engine	To collect an example dataset from which to extract information through a learning algorithm
Epistemological traits	- top-down approach - symbolic approach - deterministic prediction paradigm		- bottom-up approach - sub-symbolic approach - non-deterministic prediction paradigm

To sum up the features of the activity of the second phase of the module, the distinctive traits of the three programming approaches to AI that are presented to the students are compared in Table 1, in terms of the role that the programmer has in each of them and the epistemological traits.

Phase 3 – Bridge activities

Activity 6) Comparing neural networks and complex systems – This activity is the focus of this chapter and will be presented in detail in the next section. Its role is to set the connection (bridge) between the EKP/CK/IP part of the module and the section related to future-oriented practices.

Activity 7) Predict, hypothesize, and imagine the futures: from physics to futures studies – The transition continues with this activity that is guided by the introduction of the science of complex systems as a new paradigm to think about the future, radically different from that of classical Newtonian physics. The features of complex systems are exemplified using simulations of the Schelling's model of racial segregation (for emergent properties and non-linearity), the predator-prey Lotka-Volterra model (for non-linearity, feedback and causal circularity) and the Lorentz' model for meteorological predictions (non-linearity and deterministic chaos). During the lesson, it is pointed out that this new non-deterministic way of thinking about the future has also inspired a branch of social sciences, the *futures studies*, which considers different types of futures: probable, plausible, possible and desirable.

Phase 4 – Future-oriented activities

Activity 8) The town of Ada (analysis and scenario analysis) – The activity opens a series of team-work tasks on "the city of Ada". The students are presented a description of the town of Ada, a small, growing city that is enjoying an extraordinary season of opportunity, especially triggered by Babbage, a flourishing company which produces processors that could be used for AI developments of the city. The story of Ada ends with a proposal of automation on the basis of AI that Babbage makes to the city administration, so that the mayor has to make a decision that will affect both private and collective interests. In a first phase, the students need to identify which social, political, ethical, and economic implications can have a decision concerning AI, and which stakeholders, values and interests are involved in a decision-making process on citizenship issues. Then, the students are presented three future scenarios – a hyper technological scenario, a rural scenario and a balanced one – and have to analyze them identifying pros and cons of each and choose the preferred scenario.

Phase 5 – Action competence activities

Activity 9) The town of Ada (scenario development, backcasting and action planning) – Through this activity, the students are encouraged to imagine the town Ada where they wish to live or that they would like to visit in 2040, and to think about their roles as individuals and professionals in this future. The activity is focused on the concept of desirable future and, through action competence strategies, the students are guided to play with forecasting and back-casting activities, and to plan actions that can contribute to achieving the desirable future. During the activities the students are encouraged to imagine possible future careers and unleash their creativity.

3. The machine learning approach to Artificial Intelligence

After having presented the context of the module on AI, we analyze in more details the activity on the interpretation of neural networks as complex systems (Activity 6 of the previous list). To do this, we need to recall how the neural networks were introduced to the students in Activity 5.

Before presenting in detail the neural networks, we started from the Samuel's definition of machine learning as the field of study that gives computers the ability to learn without being explicitly programmed (Samuel, 1959). Hence, the "learning" which the machine obtains is hence reached through a bottom-up process that starts from a base of data (*database*) made of examples. Even if machine learning contains a wide range of methods, techniques, and approaches, two main paradigms can be identified:

- supervised learning: the task of the machine consists in inferring a function from labeled data. The labeled datasets are designed to train or "supervise" algorithms to solve problems of classification (assign test data into specific categories) or regression (infer the relationship between dependent and independent features of the data, usually to make predictions);
- unsupervised learning: the task of the machine consists in organizing or discovering patterns in unlabeled datasets. One of the most common application of unsupervised learning is the clustering, where the examples of the database are separated by the machine in groups basing on similarities and differences.

Focusing on the supervised learning, we analyze a very essential problem of data classification. We can consider the dataset in Figure 2 organized in a 2-dimensional space where x_1 and x_2 are the features that describe the data: they could be height and weight of a person or the size and price of a house, or many other couple of variables. In this case, we notice that it is a dataset for supervised learning since the data are labeled. We *know* that some data are circles (women or studios) and other are crosses (men or villas). In front of this dataset the task for the machine learning algorithm is to find a *good* function that separates *well* data belonging to different classes, where "good" and "well" refer to the robustness of the separations which should be generalizable to new examples. Indeed, the final objective of the algorithm should be classifying a new, unlabeled datum as cross or circle, based on the obtained separation function.

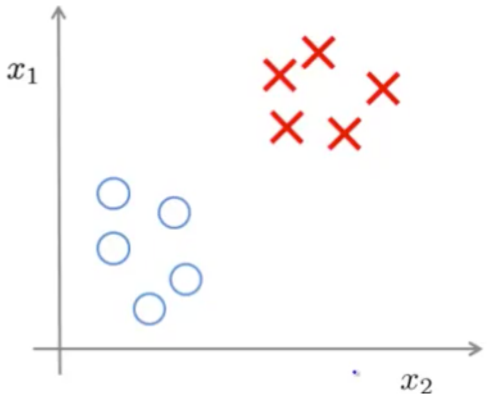

Figure 2. Labeled dataset for a classification algorithm.

Once constructed the "sense" of what a supervised learning algorithm is, we need to structure it in a more formal way. In Figure 3 we represent the flow diagram of the ingredients and steps of a generic supervised learning procedure. The starting point is a training dataset, which can be imagined as a table in which in the rows are located the different training examples (the x) and in the columns the values of the features (x_1 and x_2 following the prior example) and an additional column for the known label (cross or circle) that we will call y. The training dataset passes through a learning algorithm whose goal is to learn from the dataset a function h such that h(x) is a good predictor for the corresponding label y; this function h(x) is named hypothesis function.

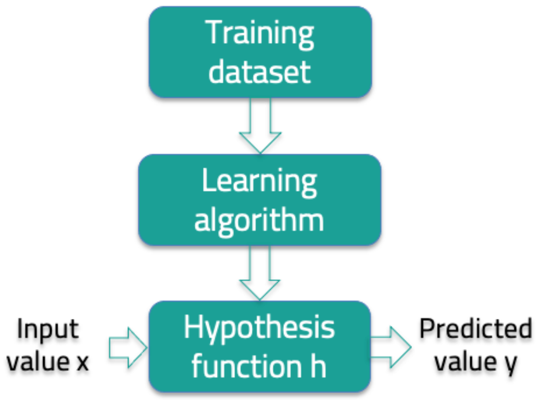

Figure 3. Flow diagram for a generic supervised learning procedure.

Among the most used hypothesis functions, there are:

- the linear hypothesis function, used in cases of linear regression: $h_\theta(x) = \theta_0 + \theta_1 x$
- the logistic hypothesis function, used in cases of logistic classification: $h_\theta(x) = \frac{1}{1+ e^{-\theta^T x}} = g(\theta^T x)$

These define the structure of the hypothesis function – determining which shape will have – but its complete definition is achieved when the θs parameters are specified. The choice of these parameters should be done in such a way that the value returned by the hypothesis function $h_\theta(x)$ is as close as possible to the label y known for the training examples (x, y). Needing to find an "as close as possible" result, the issue of choosing the parameters can be traced back to a minimization

problem, i.e. find the values of the θs parameters so that a certain "object" is minimized. This "object" is called *cost function*, whose value (the cost) is high if the prediction is very distant from the label while it is low if, on the contrary, the hypothesis function works well.
The cited linear and logistic hypothesis functions are examples for which the hypothesis and cost functions can be written explicitly in a rather easy way but is other case this cannot be done. To show it pictorially, we report and example in Figure 4. It is a classification problem similar to that in Figure 2 but, in this case, we do not have a simple known function that can separate the two classes of labeled data. One option should be using a polynomial function as that drawn in green. However, this is not a "good" hypothesis function in the sense specified above and is not recommendable for *overfitting* reasons: it corresponds so closely to the given dataset that fails to fit additional data or predict future observations reliably.

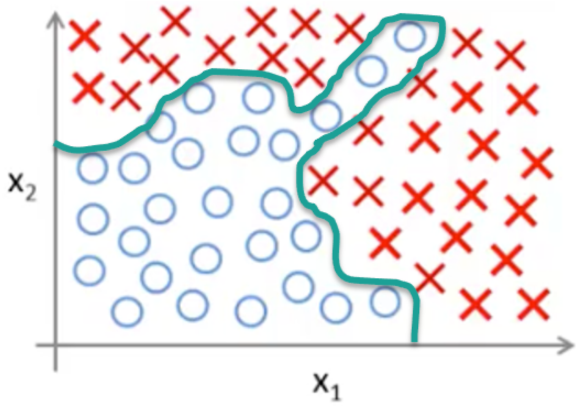

Figure 4. Labeled dataset for a classification algorithm and attempt of determination of hypothesis function (with overfitting).

In similar cases, the artificial neural networks are the algorithms needed and often used to solve these problems of classification.

3.1. The Artificial Neural Networks as a machine learning algorithm

To introduce the artificial neural networks, let's imagine having a problem of multi-class classification in which images of streets have to be automatically classified depending on if they depict a car, a motorcycle, a truck, or a pedestrian. The training dataset consists of m examples that can be written as pairs $(x^{(1)},y^{(1)})$, $(x^{(2)},y^{(2)})$, …, $(x^{(m)},y^{(m)})$ in which the first element is a vector of features' values $(x^{(i)})$ and the second contain the true corresponding label $(y^{(i)})$. In our case, the features are the values of the pixels of the image while the labels are four-component vectors: [1,0,0,0] for images of pedestrians, [0,1,0,0] for cars, [0,0,1,0] for motorcycles and [0,0,0,1] for trucks.
To describe what a neural network is, we have to consider that this family of algorithms has been developed with the aim of imitating the functioning of neuron and neuronal networks. A neuron can be modelled as a functional unit which: i) receives via the dendrites (input wires) signals that

come from other neurons or from the external world, ii) processes the signals, and iii) sends the signals processed to another neuron via the axon (output wire). A simplified biological model of neuron is reported on the left part of Figure 5.

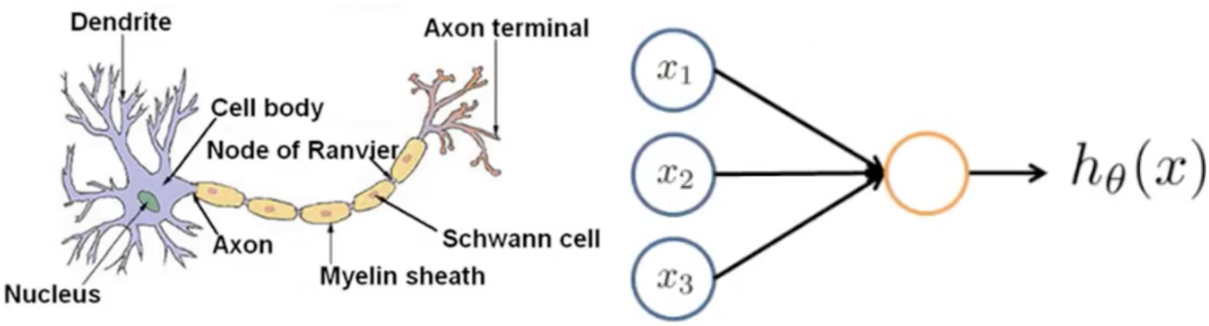

Figure 5. From the biological model of a neuron to its computational model (perceptron).

Starting from the biological model of a neuron, in 1958 Rosenblatt modelled the first, simplest artificial neural network with a single neuron as a computational unit that: i) receives a certain number of inputs, ii) carries out calculations, and iii) returns the results of the calculations (Rosenblatt, 1958). A schematic representation of the perceptron is provided in the right part of Figure 5. In our example, the inputs are the values of the pixels $x^{(i)}$ (the features) while the output is the result of the hypothesis function $h_\theta(x)$ applied on the inputs and corresponds to the prediction of the class to which the image belongs. Usually, as hypothesis function is chosen the sigmoid.

A neural network consists of many single neurons organized in layers, according to a variety of possible arrangement and resulting architectures. In the following we focus on the feed-forward neural network, characterized by the fact that the connections between the nodes cannot form a cycle and that information only flows from the input to the output. In Figure 6 we report an example of feed-forward neural network with a single hidden layer of three neurons – it is called "hidden" since it is intermediate between the input and the output.

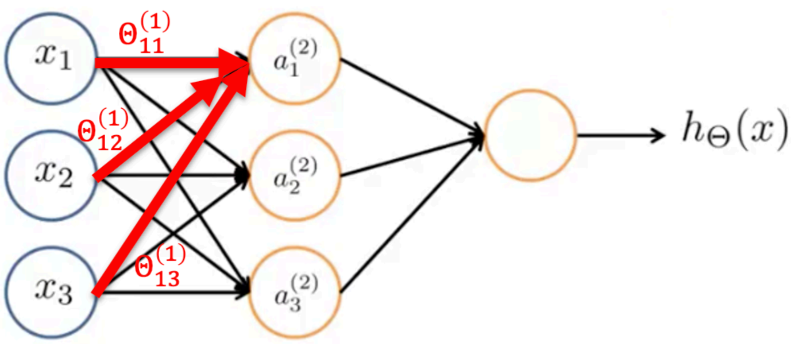

Figure 6. Schema of a feed-forward neural network with three neurons in the hidden layer.

To interpret Figure 6, some terminology is needed:

- $a_i^{(j)}$ is the "activation" of unit i in layer j, i.e. the result of application of the sigmoid function;
- $\theta^{(j)}$ is the matrix of weights mapping from layer j to layer j+1;

- $\theta_{ik}^{(j)}$ is the element of the matrix that brings from the node k in layer j to node i in layer j+1.

The calculation performed by each neuron is the computation of the sigmoid function on the scalar product between the values of the inputs and the corresponding weights. Hence, for the three neurons of the hidden layer, the calculations consist in:

$$a_1^{(2)} = g\left(\Theta_{11}^{(1)} x_1 + \Theta_{12}^{(1)} x_2 + \Theta_{13}^{(1)} x_3\right)$$
$$a_2^{(2)} = g\left(\Theta_{21}^{(1)} x_1 + \Theta_{22}^{(1)} x_2 + \Theta_{23}^{(1)} x_3\right)$$
$$a_3^{(2)} = g\left(\Theta_{31}^{(1)} x_1 + \Theta_{32}^{(1)} x_2 + \Theta_{33}^{(1)} x_3\right)$$

Then, the last neuron on the right provides the final computation of the hypothesis function, calculating the sigmoid on the scalar product between the results of the activation and the corresponding weights:

$$h_\Theta(x) = a_1^{(3)} = g\left(\Theta_{11}^{(2)} a_1^{(2)} + \Theta_{12}^{(2)} a_2^{(2)} + \Theta_{13}^{(2)} a_3^{(2)}\right)$$

From here it should be evident why the computation of the hypothesis function is called *forward propagation*, and the neural network is named *feed-forward*: the process starts with the inputs that pass to the activations of the hidden layer which forward propagate the results to compute the activations of the output layer. Moreover, we can notice the complexity of the resulting hypothesis function. What is fed into the final formula are not the features x_1, x_2, x_n which were present in the original database, but the values $a_i^{(j)}$ which are in turn the results of the computations performed by the hidden layer which are learnt as functions of the input. Therefore, $h_\theta(x)$ results a complex function, strongly non-linear.

As in the simple cases of the linear regression and logistic classification functions, once we have the mathematical form of the functions, the issue is to choose the values of the weights which characterize the connections between the nodes of the network. Even with neural networks we can use a cost function whose value increases when the distance between the computed output and the known label increases:

$$J(\Theta) = -\frac{1}{m}\sum_{i=1}^{m}\sum_{k=1}^{K}\left[y_k^{(i)} \log\left(\left(h_\Theta\left(x^{(i)}\right)\right)_k\right) + (1 - y_k^{(i)}) \log\left(\left(h_\Theta\left(x^{(i)}\right)\right)_k\right)\right] + \frac{\lambda}{2m}\sum_{l=1}^{L-1}\sum_{i=1}^{s_l}\sum_{j=1}^{s_{l+1}}(\Theta_{ji}^{(l)})^2$$

Where L is the total number of layers in the network (including input and output), s_l is the number of nodes in layer l, and K is the number of output units (usually corresponding to the number of classes to be distinguished among). Without entering the mathematic details of the cost function, to minimize the cost function J(θ) the method followed is that of the *error back-propagation*. At the first iteration, the weights θ are random initialized. The first example in the training dataset ($x^{(1)}$,$y^{(1)}$) is used to perform the forward propagation using the activation functions for the hidden layer and then for the computation of the hypothesis function of the final layer. The second step is the error calculation, comparing the known label $y^{(1)}$ with the prediction obtained with the final layer. The third and last step is to back-propagate the errors from the output layer to the hidden one, updating the ways in which that the cost function, if re-computed with the new weights, is minimum. This is repeated for all the examples in the training dataset.

After the training phase, the neural network needs to be validated and, then, tested. The validation consists in the classification of new examples varying some hyperparameters of the network (e.g. the number of hidden layers, or the number of neurons for each layer). After having set the hyperparameters, the test is done to evaluate the accuracy of the model with further examples which is computed as the fraction of the test examples for which the prediction corresponds to the label with respect to the total number of tests. This accuracy becomes a measure of the network's reliability to generalize the classification to examples which are different to those of the training dataset.

With the steps we described we have solved a problem that we were not able to describe *a priori*: because of the perceptive character of the issue of images' classification, we do not have an algorithm (as we have with tic-tac-toe) to describe top-down the steps that our brain follows to distinguish trucks and pedestrians. Moreover, differently than in the case of the imperative and logical paradigm, the solution we obtained has a probabilistic nature, since every neural network has its own accuracy. A consequence of the bottom-up character of the artificial neural network is that, even if we say that it "learnt" to solve a problem, actually this learning consists in having assigned numbers to connections between neurons, through a complex process that we named error back-propagation. To a human, those numbers are meaningless because no *symbolic* relationship exists between the values of the parameters and the decision/classification/prediction obtained by the machine. For epistemologists, this is known as the so-called black-box paradigm. As stated by Vespignani (2019, "many algorithms take an input data and produce an output, passing through a learning process that is a black box that cannot be interpreted from the outside" (p. 74). Using algorithms as the neural networks, the machines obtain implicit knowledge through examples, without making explicit and human-readable why these results are obtained. This misalignment between the outstanding results obtained with machine learning algorithms and our capability of explaining and interpreting them has been made manifest in noteworthy case studies (Kurakin, Goodfellow & Bengio, 2016; Goodfellow, Shlens & Szegedy, 2015; Su, Vargas & Sakurai, 2019). For example, in one of them, adding to an image of a panda an imperceptibly small vector, the classification of the image changes and instead of a panda the machine (which is supposed to be well-trained) returns a gibbon with a 99.3% confidence (Goodfellow, Shlens & Szegedy, 2015). These case studies are not only of specialists' interest because the neural networks' applications span a range of fields from healthcare to self-driving vehicles and their black-box nature induces a lack of trust. As stated by Doshi-Velez and Been (2017): "The problem is that a single metric, such as classification accuracy, is an incomplete description of most real-world tasks". From this crucial issue, a new field of investigation has been born: that of explainable artificial intelligence (XAI) which is developing a set of techniques, tools, and algorithms to generate high-quality interpretable, intuitive, human-understandable explanations of AI decisions. For a review of this recent but promising field, we refer to (Das & Rad, 2020; Adadi & Berrada, 2018; Molnar, 2021).

4. Interpretation of neural networks as complex systems

The core and last part of the activity about neural networks is their interpretation as complex systems. The hypothesis leading this interpretation is that the machine learning revolution shares some epistemological similarities with the revolution introduced by the science of complex systems: both imply and require a shift from classical determinism to probability, and challenge the classical definition of explanation of phenomena, because of the opacity of their models. Hence, we thought that the ML paradigm shift could be shown by developing a parallelism between neural networks and complex systems and, in particular, by recognizing in the neural networks most features of complex systems.

To establish the analogy between the neural network and a complex system, we considered the specific case of the flock of birds, an example of natural complex system the students encountered from the beginning of the teaching-learning module (in Activity 1).

If flight of birds in flocks is a phenomenon that has been manifesting to humans since mythological times, its explanation is rather recent (Bajec & Heppner, 2009). Trying to define what a flock is, in 1958 a biologist said that a flock is “two or more birds which associate with each other due to innate gregarious tendencies” (Beer, 1958, p. 78). However, this definition failed against the studies of a computer scientists, whose modelling attempts suggested that coordinated flocking may be the product not simply of “gregariousness”, but of extremely simple behavioral rules that each bird in the group follows (Reynolds, 1987). Reynolds attempted a simulation of a flock in which every bird was an agent of the system and attended the following rules, in order of decreasing precedence:

- Collision avoidance: avoid collisions with nearby flockmates;
- Velocity matching: attempt to match velocity with nearby flockmates;
- Flock centering: attempt to stay close to nearby flockmates.

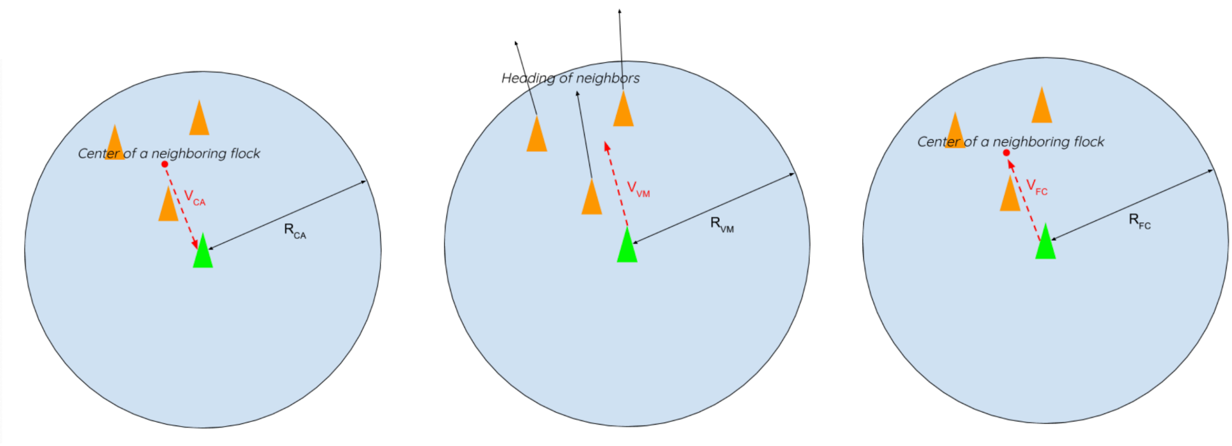

Figure 7. Graphical representation of the three rules of birds in a flock according to Reynolds (1987). The images are taken from Kang (2017).

These rules, graphically represented in Figure 7, can be implemented in an agent-based simulation as that available in the NetLogo Models Library (Wilensky, 1998). Part of code implementation is reported and commented in Table 2.

Table 2. Correspondence between the rules of the Reynolds' model for flock formation and the implementation in NetLogo "Flocking" simulation (Wilensky, 1998).

	Code	Pseudocode
General procedure	to flock find-flockmates if any? flockmates [find-nearest-neighbor ifelse distance nearest-neighbor < minimum-separation [separate] [align cohere]] end	At any tick of the simulation, each bird has to: - check if it has neighbors: - if so, select the nearest neighbor and compute its distance, - if the distance is lower than the minimum possible distance, separate the two to avoid collision, - otherwise, align the direction of motion with that of the neighbor and move towards the others
Collision avoidance rule	to separate turn-away ([heading] of nearest-neighbor) max-separate-turn end	To avoid collision (in case the distance between the focal agent and the nearest neighbor is lower than the minimum possible distance, see above) each agent has to: - turn in the direction of the nearest neighbor, - set its distance to the maximum possible value.
Velocity matching rule	to align turn-towards average-flockmate-heading max-align-turn end	To align with the nearest neighbors each agent has to: - set its direction according to the average direction of the neighbors in its range of vision
Flock centering rule	to cohere turn-towards average-heading-towards-flockmates max-cohere-turn end	To maintain the coherence with the nearest neighbors each agent has to: - set its direction according to the average position of the neighbors in its range of vision

The agent-based modelling of the flock according to the Reynolds' rules explains a wider real-world phenomenology of flocks' behavior than other more simplistic views that assume a "central force" model or a "follow the designated leader" model. For example, real flocks sometimes split apart to overcome an obstacle and the rule of flock centering allows the flock to separate since the thing that matters is that an agent remains close to its nearby neighbors, without caring if the rest of the flock turns away. Instead, a perspective which assumes that the birds follow their leader with a gregarious tendency cannot model this splitting (Bajec & Heppner, 2009).

Having introduced the main features of the flocking model as well as the characteristics of neural networks, we have all the elements to explore how the neural networks can be considered complex systems through the establishment of the analogy with the agent-based model for the flock of birds.

Five main similarities between the two systems can be identified. They are summarized in Table 3 but we analyze them in details in the following list:

- Existence of individual components of the system

The core of the agent-based modelling is that a system is not conceived as a whole, but as the set of its components, namely the agents. In the case of the flock, the individual components are the single birds, while in the case of the neural network the components are the neurons. In both cases, the evolution of the system is distributed over its components.

- Characteristics of the rules for the agents

In the Reynolds' model, each bird moves according to simple rules based on distance, speed, and density with respect to the nearest neighbours. Even if simple, these rules are non-linear since involve threshold-based decisions. In feed-forward neural networks too, the rules that each artificial neuron attends are simple, non-linear (the most common function that the neurons compute is the logistic one that is used to decide their own activation) and involve only the states of the neurons in the previous layer. In this sense, both the flock and the neural networks share the features of locality and non-linearity of the rules. Another feature that they share is the determinism of these rules for the agents: neither in the flocking model nor in the feed-forward neural model there is any reference to probability in the rules the agents attend. However, as we will see in the following, the global evolution has a probabilistic non-deterministic character.

- Display of emergent properties

In the agent-based model of a flock, the shape of a flock is not imposed to the single birds by a chief, nor by external conditions, but results from the self-organization of the individual agents which behave according to local rules. Following these rules, the system shows a transition from a disordered phase (randomly located agents with random directions and velocity) to an ordered phase were, for example, the velocities of the particles result aligned (Vicsek, Czirók, Ben-Jacob & Shochet, 1995; Cucker & Smale, 2005; Vicsek, 2008). This global behavior (uniform velocity that comes to characterize the flock as a whole) occurs as a result of the individual actions performed by the single agents which, for their changes of direction, position and velocity, only refer to their nearest neighbors and not to the whole flock. An emergent property can be recognized also in the artificial neural networks. The very same knowledge that the network acquires is not an a priori set competence but a property of the trained, validated, and tested network that emerges from simple local interactions among the agents. Like the flock, a neural network lacks a central control: the processing is distributed over the network and the roles of the neurons and weights change dynamically through a process of self-organization which has learning as its result (Cilliers, 1998).

- Presence of feedback mechanisms

The case of the flock was the example chosen by Fromm (2005) to illustrate, in its taxonomy of emergence, the case of "weak emergence". He characterizes it by identifying various types of feedbacks that involve different levels within the system (Adams & Dormans, 2012, p. 56). For example, a bird reacts to the vicinity of other birds which in turn regulate their motion accordingly to its behavior: this is a case of "agent-to-agent feedback", positioned at the local level of the system since regards the agent and its neighbors. Moreover, the movement of the flock depends on the movement of the single birds but also the trajectories of the birds happen to depend on the shape of the flock: this is an example of “group-to-agent feedback” which relates to the circular connection between the local level of birds and the global level of the flock. This feedback mechanism between the local and the global levels of the system can be recognized also in the case of neural networks. Indeed, in the training phase, with the error-back propagation, the weights of the network are assessed with a circular process that starts from the random initialization of weights, passes through the forward propagation to output, and then compares the result obtained with the label in the database, changing the weights backward accordingly. The input of the network determines the result obtained but this, in turn, lets the structure of the network change and feedbacks on the following procedures.

- Non-linear dependencies

The last commonality that we identified between neural networks and complex systems, via the comparison with the flock of birds, is the non-linear dependence between the local rules and the global behavior of the systems. In the case of the flock, the change of trajectory of a single bird may radically change the shape and trajectory of the flock. In the same way, the outputs of the network are highly sensitive to the value of the weights and, also, to the composition of the training database and to the specific data that the network is requested to classify, as the studies on adversarial examples (Goodfellow, Shlens & Szegedy, 2015) or to unfair databases have shown (Buolamwini, 2017; Kamiran, Calders & Pechenizkiy, 2012).

Table 3. Summary of the interpretation of ANN as a complex system basing on the analogy with the flock of birds.

	Neural network	Flock of birds
Existence of individual components of the system	Neurons as agents	Birds as agents
Characteristics of the rules for the agents	The rules each artificial neuron attends are simple, non-linear, deterministic and involve only the states of the previous layer of neurons	Each bird moves according to simple, deterministic but non-linear rules based on distance, speed, and density with respect to the nearest neighbors
Display of emergent property	The “knowledge” of the network is not an a priori set competence, but is a property of the net that emerges from simple local interactions among agents	The shape of the flock is not imposed to the single birds by a “chief”, but results from their self-organization
Presence of feedback mechanisms	During the training phase, the weights of the ANN are assessed with a circular input-output process	The movement of the flock depends on the movement of the single birds but also the trajectories of the birds depend on the shape of the flock
Non-linear dependencies	The outputs of the network are highly sensitive to the value of the weights	The change of trajectory of a single bird may radically change the shape and trajectory of the flock

5. Interpretation of machine learning in the light of other approaches to AI

The interpretation of the artificial neural network as a complex system, illustrated in the previous section, allows us to highlight crucial aspects that characterize the connectionist approach but that we can generalize as epistemological traits of many machine learning methods and techniques.
First, the knowledge reached by a neural network, i.e. its ability to perform a task, emerges *bottom-up* from the examples with which the network is fed, without any *a priori* expert knowledge about the task. With imperative and logical approaches to computing, knowledge on the problem is owned by the programmers who formulate the algorithms and impose their strategies to the machine that only has to apply them in the established way. The example of tic-tac-toe, carried out with the students in the I SEE module, shows the difference between the imperative and logical on one side and machine learning approach on the other in a clear way. Using the neural network, the programmers do not write any procedure for the machine to act the moves: it is the machine that trains itself "observing" winning and losing matches and, from here, learns its strategy.
Second, the existence of many individual agents and the non-linear character of interactions among them create an opaqueness of the network that directly associates to the *sub-symbolism* of such an approach. At the end of the process of training, validation and test, the knowledge obtained by the machine that it uses to produce a result, or a decision does not consist in human-readable information but only in a wide matrix of connections' weights. On the opposite, the imperative and logical paradigms are symbolic, meaning that the steps the machine follows are intelligible and can be meaningfully connected to aspects of the issue at stake. Referring once again to the example of tic-tac-toe, with an imperative or logical approach we can associate in every stage of the computation a meaning to the actions performed by the machine and, as a consequence, is rather easy to find bugs or errors in the algorithm; this is not the case of the neural network where its structure cannot be interpreted as any logical decision or procedure, without explicit and symbolic correspondence with the issue at stake.
These features of neural networks, together with the statistical characterization of the outputs, characterize the machine learning approach as a non-deterministic but probabilistic prediction paradigm, unlike the imperative and logical ones presented before in the teaching module. Instead of producing fixed results, the neural networks have their own accuracy and strongly depend on the way in which they are trained. Although this could seem a failure with respect to other, more "certain" ways of producing knowledge, the neural networks open a new way to confront machines and their "intelligence" in the light of a vocabulary of probability and uncertainty.

6. Conclusions

With this work, through the construction of the parallelism with the system of bird flocks, we have provided detailed and "technical" reasons, anchored on the mathematical and computational modelling, for the claim that neural networks are complex systems. Indeed, they i) have complex structures themselves, ii) encode information about their environment in a distributed form, and iii) have the capacity to self-organize their internal structure (Cilliers, 1998, p. 25).

However, the purpose of this work was not technical. We aimed at highlighting how complexity can be a lens to shed light into the novelty of some machine learning methods with respect to more traditional approaches to artificial intelligence like the imperative and the logical ones. Ravaioli (2020) recognized in complexity an epistemological activator since it is a *conceptual lens* to reinterpret the structure and the basic principles of the neural networks, a *criterion* to distinguish and compare the approaches to artificial intelligence, and a *new paradigm* to think about the future and the role of science and technology in the society (p. 43). Our work meant to detail all aspects of this definition and to illustrate how complexity can be a "red thread" to structure an entire module on Artificial Intelligence as that we have presented.

The I SEE module has been implemented and tested six times in different contexts with classes of 16-17 years-old student. Since its first edition in February-March 2018, the module reached about 140 Italian and Finnish students. In following implementations, we will design specific tools of data collection to investigate to which extent the students were able to appropriate the conceptual and epistemological aspects of the machine learning and neural networks, and what contributions to their learning can the perspective of complexity play.

We are aware that the module and our analysis do not comprehend all the panorama of advancements in recent fields of research. For example, only neural networks are presented, and they are treated as black boxes. If, on one side, this has allowed us to address clearly some conceptual and epistemological traits of both complexity and machine learning with students with no background in computation nor AI, it neglects the recent and already well-established works in the field of Explainable AI. While re-designing the module, it will be necessary to include the presentation of interpretable machine learning algorithms (e.g. decision trees) as well as some methods for neural networks interpretability (Molnar, 2021). This will allow to problematize and overcome the Manichean separation between symbolism and sub-symbolism, between black and "white" boxes, and between opaqueness and interpretability, allowing to dig even deeper in the *complexity* of the topic.

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Chapter 5 - The paradigm shift embodied in computational simulations of complex systems: the case study of SIR model to compare equation- and agent-based perspectives[8]

During the COVID-19 pandemic, the whole society with its stakeholders have been exposed to models and computational simulations. Indeed, these scientific tools, usually addressed to experts, were embedded in societal debates and used as a basis for making decisions and evaluating the effects of different measures of social distances to "flatten the curve". In this chapter we propose an educational analysis of one of the most popular models for the spread of diseases, that has been applied also to the case of COVID-19: the SIR model. In particular, we discuss two main approaches to simulate the SIR model, namely the agent-based and equation-based ones. We argue that SIR simulations are a very interesting case to show in teaching the change in the scientific paradigm from the Newtonian and deterministic view of science to the contemporary one based on probability, discretization, and emergence. In the analysis, we point out and discuss how such a change is mirrored in the SIR model, and the crucial details that should be stressed in teaching to highlight such a change. A special emphasis in paid to the epistemological aspects that characterize complex systems and that are implemented in the mathematical and computational SIR models. The results of the epistemological analysis will be discussed in the light of the OECD Learning Compass 2030 framework and the recent findings of literature in future-oriented science education. In particular, we will highlight the contribution of the present work to the operationalization of

[8] The contents of this chapter have been the object of an extended abstract that was selected for oral presentation at the NARST 2021 Conference (Barelli & Levrini, 2021). The work on the analysis of the SIR equation-based model and the comparison between the equation- and agent-based approaches have been the core of our co-authorship – with a team of physicists, statisticians, and medical doctors in public hygiene – in a modelling paper realized in the early stages of the pandemic to compare predictions on the hospitalizations for two regions of Italy (Reno, Lenzi, Navarra, Barelli, Gori, Lanza, Valentini, Tang & Fantini, 2020). Several educational activities have been designed based on the analysis carried out in this chapter, such as those included in the IDENTITIES' project module on COVID-19 evolution (Barelli et al., submitted).

transformative competencies, of the Anticipation-Action-Reflection cycle and of future-scaffolding skills within a specific scientific topic.

1. Introduction

The COVID-19 pandemic has not only revolutionised our behaviours as individuals but has also introduced new ways for societal stakeholders of looking at the scientific world. The on-going revolution has generated vivid debates also within science education, with the almost unanimous acknowledgement that in front of such an epochal event, the way in which we educate the youngsters and teach them science must be re-thought and re-framed (Erduran, 2020a; Blandford & Thorne, 2020; Reiss, 2020; Levrini et al., 2020). Indeed, rather than operating in an ideal and stereotyped neutral place (Bloom & Quebec Fuentes, 2020), science has been seen acting in a context of strong relationships with politics, social sciences, and economics (Erduran, 2020b). Moreover, for the first time in recent history, not only the products of science, like drugs, treatments, or vaccines, but mainly its processes and practices have been exposed to the public, leading people to see science in its development. Terms like models and simulations, that have been routines for scientists in many fields for many years but mostly unknown to non-expert stakeholders, are nowadays part of the popular vocabulary, addressed during talk shows and news, on television, journals, and social media channels. In recent history, despite the increasing attention to the climate change issue, humanity had never faced a challenge that was perceived so urgent by everyone all around the world. At the same time, the scientific community, despite the complexity of the problem, could count on advanced devices and tools. Recent advances in computational tools, public data sharing, and better visualization methods caused the topic of infectious diseases modelling and simulations to get more attention from citizenship, governments and media than for any previous global challenge (McBryde et al., 2020).

However, the extensive debate on the contribution of models and simulations to orient social behaviors, made urgent by the emergency circumstance, does not only require a strictly technical-scientific perspective to be understood and addressed. Indeed, these debates have let social and community-based ways of conceiving risk and uncertainty emerge, that also social sciences and education can help to read through their conceptual, epistemological, and critical perspectives (Brown, 2020; Pietrocola, Rodrigues, Bercot & Schnorr, 2020; Weible et al., 2020). Among many others, the concept of probability has become of outstanding importance to understand, for example, the difference between predictions and projections - the former indicating an operation of deterministic extrapolation of past and present trends, the latter suggesting a multiplicity of scenarios and possibilities. It is also crucial for the correct interpretation of one of the most cited measures of pandemic: the basic and effective reproduction numbers, R_0 and R_t (Natalini, 2020). Another important issue that the societal discussion about models and simulations has contributed to raise is the role of individuals to affect global – or at least community – phenomena. In particular, the possibility to observe the results of simulations that reported the domino effect of the spread of a virus has challenged the linear thinking that usually rules our understanding of cause-effect relationships but does not hold when complex, exponential phenomena are involved (Kache & Mrowka, 2020).

While driving the world's response to the pandemic (Adam, 2020), we claim that simulations can be an invaluable resource also within science education. Even if they are already used in most classrooms at many school levels as interactive learning environments (de Vries & Huisman in Kirschner & Huisman, 1998), very seldom they are addressed for the authentic meaning they have within the scientific community (Greca, Seoane & Arriassecq, 2014). Nevertheless, the pandemic could be the starting point to address scientific simulations as a new form of scientific production (Galison, 1996; Winsberg, 1999), with its methods and epistemology. Indeed, analysing them from an epistemological perspective, simulations can contribute to open new perspectives on foundational debates: what is the role of mathematical modelling to understand the world?, how simulations differ from mathematical models or experiments?, what is the relationship between models and theory?, what does it mean to explain a physical phenomenon through a model, a theory or a simulation?, what do different approaches to simulations reveal about the same model?.

The educational relevance of simulations for tackling with the issues raised by COVID-19 pandemic can also be read in the light of the Anticipation-Action-Reflection (AAR) cycle and the Transformative Competencies, recently included in the OECD Learning Compass 2030 (OECD, 2019). This framework sets out an aspirational vision for the future of education, in which students of all ages are requested to learn to navigate the complexity of a fast-changing world, rather than simply receiving fixed directions from instructors. Within this perspective, the final goal of education is anchored to the principle of student agency, i.e. students should become able and willing to positively influence their own lives and the world around them. To this aim, equipped with a set of knowledge, skills, attitudes and values, students must be guided to develop transformative competencies (create new value, reconcile tensions and dilemmas, take responsibility) and engage in an iterative learning process where the anticipation of the future, action and reflection feedback on each other. The same principles are at the basis also of a framework recently developed within science education that has elaborated on the skills that students need to tackle with the complexity of our evolving society. The skills have been named future-scaffolding skills (Levrini, Tasquier, Branchetti & Barelli, 2019; Levrini et al., 2021) and "refer to the capability of organising knowledge in the present, imagining futures and moving dynamically and consciously, back and forth, globally locally, between different time dimensions" (Levrini et al., 2019, p. 2667). Despite their general character that partially resembles the skills and competencies of the OECD framework, future-scaffolding skills can be developed through science education. Indeed, at their back lies the assumption that disciplines, if properly addressed valuing their conceptual and epistemological heritage, can be a context to teach and learn how to deal with complex societal issues of the present with an eye on the horizon and act as conscious citizens.

In this chapter we want to show how an epistemological reflection based on the analysis of computational models and simulations contributes to articulate the general recommendations coming from the world of education. To this aim, we examine the crucial details of computational models and simulations that emerge from the comparison between two approaches to simulation: equation- and agent-based. In particular, we want to discuss an educational approach to the case study of the SIR (susceptible-infectious-recovered) model, applied also to the case of COVID-19, as an example that allows a teacher to point out relevant crucial details to show the change in the scientific paradigm from the Newtonian and deterministic view of science to the contemporary one based on probability, discretization and emergence.

The work is structured as follows. In section 2, we present the framework about simulations in science and in education, with a special reference to the distinction between equation- and agent-based approaches to modelling and simulations. In section 3, we discuss the methods for the elaboration of our educational analysis. In section 4 we present the literature review on the comparison between equation- and agent-based models from which we derive the three criteria of comparison between the two approaches. Then, we present the educational analysis of the SIR model for the spread of diseases (section 5) and of the equation- and agent-based approaches to its simulations (section 6). In section 7 we elaborate a comparison across three epistemological categories derived in section 4 to the SIR model, framing the analysis within the wider literature on equation- and agent-based simulations. In the last section we discuss the results of the epistemological analysis in the light of the OECD Learning Compass 2030 through the lens of future-scaffolding skills, highlighting the contribution of the present work to the operationalization of transformative competencies and of the AAR cycle within a specific scientific topic.

We inform the reader that, in presenting the SIR model and its various implementations, we will provide some mathematical and computational details, mainly collected in tables. However, we will highlight the crucial points relevant for the argumentation in the main body and we will discuss them from a conceptual and epistemological point of view: for their understanding, no technical knowledge is required.

2. Framework

Simulations are nowadays a prominent topic in many disciplines. To cite few remarkable examples in three very different fields of research, simulations are used in quantum physics to address many-body problems, in medicine to pave the way to individual diagnostics and therapy, in social sciences to study the emergence of complex social phenomena like terrorism and racial segregation. In the field of education, with the same term of simulation authors have usually referred to multimedia tools used with novices to favour their understanding of topics of interest. Adopting the categorization provided by Greca and colleagues (2014), in the followings we will distinguish among two meanings of simulation: with *scientific simulations* we will refer to the simulations used in disciplinary research, while with *educational simulations* to those used mainly for didactical purposes. In the following paragraphs, we will address the main features of both the types.

2.1. Educational simulations

Within science education, simulations are usually referred as educational simulations. Following the definition by de Vries and Huisman, “a simulation is an interactive learning environment in which a model simulates the characteristics of a system on the basis of actions made by the student” (de

Vries & Huisman in Kirschner & Huisman, 1998, p. 671). Since the ‘80s, educational simulations have been used to simulate processes in many different scientific areas but also to simulate the execution of virtual experiments that it would be impossible - because too expensive, too risky or too time-demanding – to perform in school laboratories. In this sense, the site PhET Colorado (www.phet.colorado.edu) is a collection of many educational simulations in chemistry, mathematics, physics and biology for many instructional levels. All the simulations are equipped with illustrative materials that explain how they work and with proposal for teachers to use them in the classrooms. Another famous programming environment for the use and development of simulations is NetLogo (www.ccl.northwestern.edu/netlogo). As the PhET project, NetLogo includes simulations from a variety of disciplinary field, from social sciences to epidemiology. The main difference is that NetLogo is particularly well suited for modelling complex systems with an agent-based approach (that we will extensively describe in section 2.3). Moreover, NetLogo is not only a platform where simulations are available to learners, but it is a “low threshold and no ceiling” programmable environment, in which the users can create their own models.
The field of educational research comprehends many works on the limits and potentials of these tools (Smetana & Bell, 2012; Scalise et al., 2011). The main findings are that it is important to use simulations alongside with laboratory experiment and lectures, but applets *per se* are not sufficient to foster effective learning. In particular, educators need to encourage the students to take active reflections on simulations (Smetana & Bell, 2012).

2.2. Scientific simulations

For scientific research, the introduction of computational simulations has been claimed to be “a significant and permanent addition to the methods of science” (Humphreys, 2004) and compared for importance to the invention and use of instruments like microscope or telescope (Greca et al., 2014). Terms like “instrument”, “tool”, “method” often recur when authors describe the use of simulations in the sciences. Of course, as computational artifacts, they are rather recent objects that have flanked traditional scientific practices like experiments and models. However, considering simulations merely as a new tool of science would neglect the important role they have played for epistemology of science. Indeed, they have been a new way to produce knowledge about the world (Galison, 1996), to question nature and to formulate possible explanations (Grune-Yanoff & Weirich, 2010).
The philosophical literature on simulations has increased dramatically during the past 40 years and many attempts have been made to provide definitions of simulations (Grune-Yanoff & Weirich, 2010). We report here the definition provided by Paul Humphreys, an author who has worked a lot on discussing the novelty of simulations with respect to models, theories and experiments.

> *System S provides a core simulation of an object or process B just in case S is a concrete computational device that produces, via a temporal process, solutions to a computational model […] that correctly represents B, either dynamically or statically. If in addition the computational model used by S correctly represents the structure of the real system R, then S provides a core simulation of system R with respect to B. (Humphreys, 2004, p. 110)*

This definition distinguishes different plans involved in the conceptual process of simulating. From one side we have the real system R we want to model and simulate. Then, there is the model B, elaborated on the system R. On the basis of this model B, a computational model is realized (we will name it C) and on it the simulation S acts by producing, via a temporal process, its solutions. According to this definition, the "correctness" of a simulation depends on two factors: the relation between the real system R and the model B, and that between the model B and the computational model C. The meaning of the term "correctly" depends on the purpose for which the simulation is realized. Another element on which Humphrey's definition insists is the goal of a simulation, that is to *solve* a computational model, finding its solutions. Hence, using computational simulations is particularly meaningful whenever there are not analytical methods that allow to solve explicitly a given model.

2.3. Equation-based and agent-based simulations

The traditional method to solve mathematical models consists in finding an analytical solution for a set of equations. However, when this is not possible other approaches are needed.

The first approach we analyse is the equation-based one. According to this approach, the system is described through differential equations. When analytical solutions are not available or highly costly – for example for non-linear differential equations – numerical methods are used. These methods are implemented from the simulation and allow to solve step by step the model, obtaining the evolution of a system depending on the initial conditions. The evolution of the system is deterministically derived: from the present state, the numerical methods used by the simulation lead to the future state of the target system in a univocal and pre-determined way. This means that multiple runs of the same simulation, starting from the same initial conditions, produce the same results. Another important feature of equation-based simulations is that, in the computational model, only macroscopic, global variables appear. There is no reference to the single components of the system because it is modelled as an undifferentiated whole, essentially continuous. The properties of the system that are considered by the modelist relevant for its description are summarized in the equations in the form of "rate" variables which describe simultaneously the whole system. Typical example for the equation-based approach is the Lotka-Volterra's model, elaborated to describe the evolution dynamics of an ecosystem in which two species interact, one as a predator and the other as a prey (Volterra, 1928). The mathematical model consists of a pair of ordinary differential equations which describe how the sizes of prey and predator population change over time depending on some parameters[9]. The simulations of the model show the periodic

[9] The system of differential equations is:

$$\frac{dX}{dt} = \alpha x - \beta xy$$
$$\frac{dY}{dt} = \delta xy - \gamma y$$

evolution of the two populations: the growth of the prey population leads to the growth of the predator population, that in turn causes a reduction of the prey population, that in turn makes the predator population decrease.

The agent-based approach is very different. The initial step of the simulation process consists in defining and creating the minimal components of the system (they can be for example the individuals in a population) which are named the *agents* of the model. To each agent is associated a set of local rules that determine its behaviour in the interaction with the other agents and with the simulated environment. Agents are heterogenous, since they can have different attributes and different rules associated, and autonomous, since their interactions are determined exclusively by the rules assigned to them. From these interactions among the individual components and the consequent "evolution" of the agents, the evolution of the system emerges and can be observed in patterns and regularities at the macroscopic level. This feature of agent-based models and simulations is referred as their bottom-up character or, following Keller (2003), "modelling from above", since there is not a mathematical theory governing the behaviour of the agents. The macroscopic way in which the aggregate system evolves is not a-priori known nor coded but is the result of the relatively simple actions of many single entities that interact at the microscopic level.

A famous example for the agent-based approach is the model for segregation, developed by the economist Thomas Schelling to investigate the origin of zones with racial prevalence in the cities (Schelling, 1971). In this model, two types of agents are defined (e.g. black or white) and they move on a rectangular grid on the basis of a simple rule: if the percentage of similar neighbours is lower than a certain threshold, the agent changes its location randomly and occupies an empty cell of the grid. Making the system evolve with a simulation until every agent is satisfied with its location, an emergent behaviour is displayed. If, in a system, agents have even a mild intolerance toward a group they are not part of, the result is a segregation of the agents of two groups that end up occupying different zones of the grid.

2.4. Equation-based and agent-based simulations in science education

In science education, equation-based and agent-based simulations are mainly introduced when complex systems are addressed. In particular, they are used when the science complex system is emphasized as the discipline that studies how behaviour of phenomena at different scales is related to the interdependent components at lower scales (Bar-Yam, 2016). This should already recall the distinction between equation- and agent-based modelling addressed above in terms of their top-down vs bottom-up character.

Equation-based and agent-based models and simulations have also become a way within educational research to address in teaching different forms of reasoning about dynamic systems, with special regard to the formulation of explanations (Jacobson & Wilensky, 2006). The first form

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where X is the size of prey population, Y the size of predator population, α the birth rate of the prey population, β the meeting rate between preys and predators, γ the death rate of the predator population, δ the predation rate.

of reasoning is positioned on a “macro” level: the focus is on the system conceived as a population (sometimes as composed of different groups) with its own macroscopic properties that evolve over time according to rates of change, for example of transitions between groups. On the contrary, the second form of reasoning acts at a “micro” level: the attention is on the minimum elements of the system, the agents, which interact according to local rules. Here, we can easily recognize the parallelism between these two levels of reasoning and the features of equation- and agent-based simulations described in section 2.3. Traditional mathematical and science education mainly encourage aggregate reasoning, also through the introduction of differential equations as descriptive tools of dynamic systems. More recently, since the 90s, importance of agent-based reasoning has been emphasized within education as a way to foster understanding on the systems and to enter the mechanistic dimension of local interactions (Wilensky & Reisman, 2006). Nowadays, the two forms of reasoning are considered both essential to reach a profound understanding of complex systems and in particular to comprehend the emergence of global patterns and behaviours from the local interactions among agents. This concept has been expressed as the “embedded complementarity” of aggregate and agent-based reasoning (Stroup & Wilensky, 2014). Even if they have their own very different features, they are not incompatible, nor necessarily working against one other. On the opposite, they are complementary for reaching a mature reasoning about emergent phenomena in complex systems. Moreover, this complementarity is “embedded” because it requires not to consider the two forms of reasoning as juxtaposed, but to move from one to the other, in a dynamic mutual relationship where elements of connection can be pointed out. Several strategies can be found to connect aggregate and agent-based reasoning: Levy and Wilensky (2008) have identified relevant at this account the construction of mid-level groups, that are in-between the level of the agents and that of the emergent property. Barth-Cohen (2018) has instead focused on the role of transitional explanations between microscopic and macroscopic levels of the system.

In the following sections we will present an educational analysis of the SIR model for the spread of a disease. Beside the relevance of the topic for the current pandemic emergency, we have chosen this topic as an example of a problem that involves a complex system in which macroscopic properties can be observed, explained, and derived both from a mathematical, aggregate point of view and from an agent-based perspective. In this way, we aim to contribute to the debate within science education about the comparison between equation- and agent-based modelling. We will not explicitly address the topic of learners’ forms of reasoning about the complex phenomenon, but we will provide hints to characterize them from an epistemological perspective.

2.5. OECD Learning Compass 2030 and future-oriented science education as frameworks to exploit the educational potential of equation-based and agent-based simulations

Fostering students’ agency in an increasingly complex world is an outstanding issue for the educational researchers’ community at large and, more specifically, within science education (Hodson, 2003). Some scholars relate the development of action competences to the capacity of interpreting present trends and challenges and facing the future with its uncertainties and dilemmas. It's actually emerging a field referred as *future-oriented science education* in which different ways to anticipate the future, reflecting on alternatives and planning responsible actions are addressed in science teaching (Paige & Lloyd, 2016; Levrini et al., 2019; Levrini et al., 2021). The recent works of the research group in STEM education of the University of Bologna pointed out specific future-oriented competences that science education can contribute to foster: they are called future-scaffolding skills, whose definition is reported in Table 2.

Table 2. Definition of future-scaffolding skills (Levrini et al., 2021).

Structural skills	
St1	Distinguish between disciplinary details and the comprehensive picture of the future-oriented scientific issue (FoSI)
St2	Unpack the FoSI in simpler, addressable parts
St3	Recognize causal relationships
St4	Recognize multiple aspects of the problems and their relationships (e.g. distinction between problems, objectives, solutions or between pros and cons) for structuring proper thoughts and articulate strategies and plans for solving them
Dynamical skills	
Dyn1	Move from thinking locally to thinking globally (and vice versa)
Dyn2	Move from thinking at the present to thinking at the future (and vice versa)
Dyn3	Move from thinking at the individual to thinking at the societal community and/or the other stakeholders
Dyn4	Think creatively for imagining new possibilities and concrete actions
Dyn5	Balance the need of aspiring and desiring, and that of keeping feet on the ground
Dyn6	Think in a multidisciplinary way, breaking down the barriers among disciplines
Dyn7	Move from thinking in terms of necessity to thinking in terms of multiple possibilities

We observed that engaging in the activities of modules on future-oriented scientific issues, the students were able to develop through the module a set of skills that we organized in two macro-categories. The four structural skills are abilities to organize pieces of knowledge and build systemic views (an intentional and conscious process of scaffolding) while the seven dynamical ones are abilities to navigate across the complexity of knowledge, without trivializing the relations between local details and global views, the relations between past-present-future, and the role of individual and collective actions. These skills were named and recognized as future-scaffolding skills since the structural ones build a rational scaffolding of the topic by recognizing the causal, temporal, and logical relationships among them while the dynamical skills allow to navigate across the scaffolding for developing scenarios, visions, and creative ideas for the future (Levrini et al., 2021, p. 21). The development of these future-scaffolding skills can be the basis for trigger students' agency.

Students' agency has been object also of the recent framework elaborated by the OECD Future of Education and Skills 2030 project (https://www.oecd.org/education/2030-project/): the OECD Learning Compass 2030 (OECD, 2019). The core idea, embodied in the metaphor of the compass, is to empower learners of all ages to "navigate by themselves through unfamiliar contexts, and find their direction in a meaningful and responsible way" (OECD, 2019, p. 20). To do that, the framework identifies several components of the compass: core foundations, knowledge, skills, attitudes and values, transformative competencies and a cycle of anticipation, action and reflection (AAR). They are graphically displayed in Figure 1. For the purposes of our analysis, we will focus on the AAR cycle and the transformative competencies.

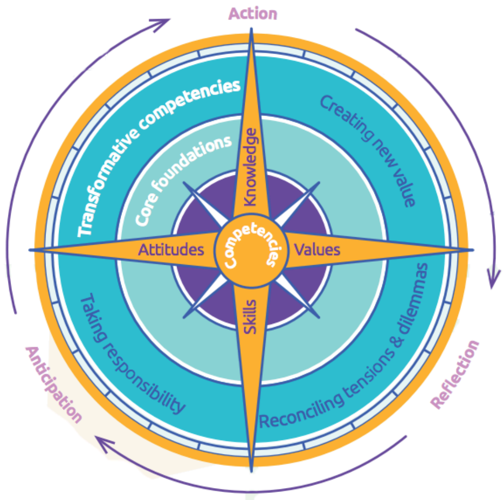

Figure 1. Representation of the OECD Learning Compass 2030 framework (OECD, 2019).

The AAR cycle is conceptualized as "an iterative learning process whereby learners continuously improve their thinking and act intentionally and responsibly, moving over time towards long-term goals that contribute to collective well-being" (OECD, 2019, p. 120). This process is articulated in three phases that inform, complement, and strengthen each other. The phase of Anticipation consists in imagining the future and thinking about how actions taken today might have consequences tomorrow; the focus is not on the *prediction* of the future (as a term like forecast would suggest) but on the envision of multiple scenarios (Poli, 2010). The next phase of the cycle is where learners take Action towards specific objectives and contribute positively or negatively to the individual or societal well-being. In the Reflection phase, learners improve their thinking and consequently reach a deeper understanding and become able to plan more responsible actions.

Engaging in such a rich process as the AAR cycle, knowledge, skills, and competencies are needed. Among them, OECD has identified three transformative competencies: creating new value, reconciling tensions and dilemmas, taking responsibility. Creating new value is related to the capacity of creating innovation (e.g. creating new jobs, developing new knowledge, applying them to problems both old and new). Reconciling tensions and dilemmas means considering the interconnections between distant ideas, logics, and positions, and using this understanding to find solutions to dilemmas and conflicts. Finally, taking responsibility is connected to the ability to reflect upon one's own actions in light of one's experience and education, and by considering personal, ethical and societal goals.

3. Methods and research questions

In this chapter we conduct an analysis of the SIR model and its simulations. The analysis articulates across three dimensions: conceptual, epistemological, educational. The conceptual dimension is involved when disciplinary aspects of the SIR model and simulations are presented and described in their technical details. The epistemological dimension is touched when the conceptual details are read in the light of debates from the philosophy of science; in the epistemological analysis, emphasis is given to the distinction between the layers of a simulation presented in section 2.2, and to the comparison between equation- and agent-based simulations. To this extent we will present a literature review on papers discussing, in different fields, the comparison between equation- and agent-based modelling, and we will extract from them categories of comparison that will become the lenses for the following analysis. The educational dimension permeates the whole work in several ways. Firstly, the disciplinary contents are presented to guide also a non-specialistic audience to the understanding of the topic and can be adapted to many school and university levels. Secondly, the results of the conceptual and epistemological analysis are interpreted in the light of educational frameworks. Indeed, it is stressed the contribution of the disciplinary and epistemological analysis to foster citizenship skills, through the engagement with the Anticipation-Action-Reflection cycle (OECD, 2019), and through the development of transformative competencies (OECD, 2019) and future-scaffolding skills (Levrini et al., 2019; Levrini et al., 2021). In section 8 we will discuss to which extent our analysis relates and contributes to the OECD educational framework, and how highlighting the distinction between different approaches to the SIR model can contribute to address the general concepts of the Learning Compass within science and mathematics education.

The three-pronged analysis has been guided by three research questions:

- RQ1. Which conceptual differences can be identified between equation- and agent-based approaches when applied to the SIR model?
- RQ2. How do equation- and agent-based simulations of the SIR model differ from an epistemological point of view?
- RQ3. What contribution can the distinction between equation- and agent-based approaches provide to foster anticipation, action, reflection, transformative competences, and future-scaffolding skills through science education?

As we mentioned, the core of the chapter is the comparison between equation- and agent-based approaches to simulation of the SIR model. To build the analytical lenses to establish this comparison, we performed a literature review. It allowed us to identify three categories of comparison as our epistemological lenses to explore the comparison of equation- and agent-based approaches to the SIR model. The methodological steps followed for the review will be provided in section 4. We emphasize since now that the choice of the three categories is not the only one that could have been done in general. The variety of criteria of comparison identified from the literature reviews shows this point very clearly. The three categories that we will use in our analysis are selected on the light of our educational goal i.e., the exploitation of AAR and transformative competences as well as future-scaffolding skills through disciplinary-grounded teaching and learning that can be addressed also at high-school level.

4. Comparison of equation- and agent-based models and simulations: from the literature review to the analytical lenses

In this section, we construct the analytical lenses to compare equation- and agent-based approaches through a literature review.

4.1. Construction of the database of papers

The first step of the literature review consisted in constructing a database of papers to analyse. We decided to focus on papers that explicitly mentioned in their title the comparison between agent- and equation-based models or simulations. The queries were run on Google Scholar in 2022, between February 4th and February 10th with the following strings: 1) “equation based agent based”; 2) “equation agent based”; 3) “equation agent based compare”; 4) “equation agent based comparison”; 5) “EBM ABM”; 6) “EBS ABS”; 7) “equation agent based simulations”; 8) “equation agent based models”. No temporal range was selected to obtain all the possible papers.
As a methodological choice, we did not restrict our analysis to the case of epidemiological modelling – even though, in the end, they resulted to be most of our papers. In this way, we obtained articles in the field of economics, management, ecology, and operational research. The database obtained consisted of 13 papers that we report in Table 3 with authors and year, title, and disciplinary field of reference.

Table 3. List of papers considered for the literature review on the comparison between equation- and agent-based modelling.

ID	Authors	Year	Title	Disciplinary field
[1]	H. Van Dyke Parunak Robert Savit Rick L. Riolo	1998	Agent-Based Modeling vs. Equation-Based Modeling: A Case Study and Users’ Guide	Economics
[2]	Yi Sun Liang Cheng	2005	A Survey on Agent-Based Modelling and Equation-based Modelling	Epidemiology
[3]	Ryan C. Kennedy Xiaorong Xiang Thomas F. Cosimano Leilani A. Arthurs Patricia A. Maurice Gregory R. Madey Stephen E. Cabaniss	2006	Verification and validation of agent-based and equation-based simulations: a comparison	Physics; Economics
[4]	Georgiy V. Bobashev D. Michael Goedecke Feng Yu Joshua M. Epstein	2007	A hybrid epidemic model: Combining the advantages of agent-based and equation based-approaches	Epidemiology
[5]	Hazhir Rahmandad John Sterman	2008	Heterogeneity and Network Structure in the Dynamics of Diffusion: Comparing Agent-Based and Differential Equation Models	Epidemiology

[6]	Till Grüne-Yanoff Paul Weirich	2010	The Philosophy and Epistemology of Simulation: A Review	Epistemology
[7]	Sreenivas R. Sukumar James J. Nutaro	2012	Agent-based vs. Equation-based Epidemiological Models A Model Selection Case Study	Epidemiology
[8]	Elizabeth Bruch Jon Atwell	2013	Agent-Based Models in Empirical Social Research	Social Sciences
[9]	Suliza Sumari Roliana Ibrahim Nor Hawaniah Zakaria Amy Hamijah Ab Hamid	2013	Comparing Three Simulation Model Using Taxonomy: System Dynamic Simulation, Discrete Event Simulation and Agent Based Simulation	Operational research
[10]	Wei Duan Zongchen Fan Peng Zhang Gang Guo Xiaogang Qiu	2014	Mathematical and Computational Approaches to Epidemic Modeling: a Comprehensive Review	Epidemiology
[11]	Elizabeth Hunter Brian Mac Namee John Kelleher	2018	A Comparison of Agent-Based Models and Equation Based Models for Infectious Disease Epidemiology	Epidemiology
[12]	Nicolas Marilleau Christophe Lang Patrick Giraudoux	2018	Coupling Agent-Based with Equation-Based Models to Study Spatially Explicit T Megapopulation Dynamics	Ecology
[13]	Claudius Gräbner Catherine S. E. Bale Bernardo Alves Furtado Brais Alvarez-Pereira James E. Gentile Heath Henderson Francesca Lipari	2019	Getting the Best of Both Worlds? Developing Complementary Equation-Based and Agent-Based Models	Economics

4.2. Extraction of the criteria of comparison between equation- and agent-based modelling

The second methodological step of the review consisted in reading the selected papers and extract, for each of them, a list of features that the authors use to distinguish between equation- and agent-based approaches to modelling and simulations. In this phase we tried to stay as close as possible to the words used by the authors. The result of this phase was a list of 31 criteria. In Table 4 we report the list of criteria mentioned by each paper.

Table 4. Criteria of comparison between equation- and agent-based approaches mentioned by each paper.

ID	Paper	Criteria of comparison
[1]	Van Dyke Parunak, Savit & Riolo, 1998	1) Emulation vs evaluation 2) Relationship between individuals and observables 3) Microlevel vs macrolevel 4) Adaptability 5) Verisimilitude 6) Stochasticity vs determinism
[2]	Sun & Cheng, 2005	1) Computational intensiveness 6) Model construction

		2) Homogeneity vs heterogeneity 3) Accurateness 4) Interaction among individuals 5) Network structure	7) Most appropriate domain 8) Continuous vs discrete (individuals) 9) Continuous vs discrete (time)
[3]	Kennedy et al., 2006	1) Performance of validation techniques	2) Stochasticity vs determinism
[4]	Bobashev et al., 2007	1) Stochasticity vs determinism 2) Complex relationships and interactions 3) Tractability	4) Adaptability 5) Bottom-up 6) Computational intensiveness
[5]	Rahmandad & Sterman, 2008	1) Homogeneity vs heterogeneity 2) Computational intensiveness 3) Stochasticity vs determinism	4) Response to metrics 5) Continuous vs discrete (individuals)
[6]	Grüne-Yanoff & Weirich, 2010	1) Microlevel vs macrolevel 2) Generate calculate	3) Homogeneity vs heterogeneity
[7]	Sukumar & Nutaro, 2012	1) Homogeneity vs heterogeneity 2) Microlevel vs macrolevel 3) Computational intensiveness 4) Interaction among individuals 5) Continuous vs discrete (time)	6) Complex relationships and interactions 7) Practical use 8) Decision support
[8]	Bruch & Atwell, 2013	1) Stochasticity vs determinism	
[9]	Sumari et al., 2013	1) Microlevel vs macrolevel 2) Top down bottom up	3) Interpretability 4) Computational intensiveness
[10]	Duan et al., 2014	1) Microlevel vs macrolevel 2) Homogeneity vs heterogeneity 3) Computational intensiveness	4) Simple complex 5) Simple detailed
[11]	Hunter, Mac Namee & Kelleher, 2018	1) Computational intensiveness 2) Homogeneity vs heterogeneity 3) Detailed information on the spread 4) Adaptability	5) Complex relationships and interactions 6) Stochasticity vs determinism 7) Interpretability
[12]	Marilleu, Lang & Giraudoux, 2018	1) Homogeneity vs heterogeneity 2) Spatial description 3) Tractability	4) Microlevel vs macrolevel 5) Computational intensiveness 6) Top down bottom up
[13]	Gräßner et al., 2019	1) Distributed vs centralized computations 2) Stochasticity vs determinism 3) Explainability	4) Complex relationships and interactions 5) Top down bottom up

4.2. Grouping the criteria of comparison into categories

After the analysis on the individual papers, we noted that the list of criteria obtained presented some superpositions. For example, many criteria identified in the papers regarded, in different ways, the complexity of interactions modelled according to the different approaches:

- Relationships and interactions: "The correlations help to show that ABM captures more complex relationships and interactions between variables than the equation based model"[10] (Hunter, Mac Namee & Kelleher, 2018)
- Interaction among individuals: "No/Invisible in equation-based modelling vs Yes/Visible in agent-based modelling" (Sun & Cheng, 2005)
- Complexity of relationships: "On the other hand, the ability of EBMs to represent the real world is usually more restricted than that of ABMs. Due to tractability considerations, EBMs have fewer dimensions than ABMs. That is, EBMs require a greater reduction of complexity and include fewer variables than ABMs. This means that the ability of EBMs to represent reality is more restricted, and that they can be explored in fewer dimensions than ABMs. In particular, there are certain mechanisms that are very difficult to represent in an EBM" (Gräßner et al., 2019)

In this case, these three criteria were grouped into the same category named "Description of interactions".

Another grouping that deserves a comment is that related to the features of the two approaches that regard their performance with respect to specific metrics or goals:

- Most appropriate domain: "For equation-based modelling, the most appropriate domains are systems that can be modelled centrally, and in which the dynamics are dominated by physical laws; for agent-based modelling, the most appropriate domains are systems with high degree of localization and distribution, dominated by discrete equations" (Sun & Cheng, 2005)
- Performance of validation techniques: "Traditional verification and validation approaches used for discrete-event system simulations are often not fit for complex newer agent-based models" (Kennedy et al., 2006)
- Response to metrics: "More interestingly, the DE and mean AB dynamics differ for several metrics relevant to public health, including diffusion speed, peak load on health services infrastructure, and total disease burden" (Rahmandad & Sterman, 2008)
- Practical use: "EBM are used for evaluation of what-if scenarios; ABM are used for observing patterns of emerging behavior" (Sukumar & Nutaro, 2012)
- Decision support: "EBM give support to decisions in operation, ABM in planning" (Sukumar & Nutaro, 2012)

For the purposes of our review – that, we recall, is oriented to the educational reconstruction of the SIR model – we grouped all these nuances in the same category of comparison named "Performance".

[10] In this section we make extensive use of citations from the papers considered for the literature review. Some authors do not use the same spelling that we chose to indicate *equation-based* and *agent-based* models, approaches, or simulation. We decided not to change the original citations and we provide here a list of the main abbreviations used: AB or agent based = agent-based; ABM = agent-based model; EB or equation based = equation-based; EBM = equation-based model; DE = differential equation; PDE = partial differential equation; ODE = ordinary differential equation.

After merging similar nuances of the distinguishing features avoiding redundancies, we obtained a list of nine criteria of comparison that we summarize in Figure 2.

	Van Dyke Parunak, Savit & Riolo, 1998	Sun & Cheng, 2005	Kennedy et al., 2006	Bobashev, Goedecke, Yu & Epstein, 2007	Rahmandad & Sterman, 2008	Grüne-Yanoff & Weirich, 2010	Sukumar & Nutaro, 2012	Bruch & Atwell, 2013	Sumari, Ibrahim, Zakaria & Ab Hamid, 2013	Duan, Fan, Zhang, Guo & Qiu, 2014	Hunter, Mac Namee & Kelleher, 2018	Marilleu, Lang & Giraudoux, 2018	Gräbner et al., 2019	
Criteria of comparison	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	Total
Computational intensiveness		■		■	■		■		■	■	■	■		8
Relationship between system's levels	■			■		■	■		■	■		■	■	8
Probabilistic nature	■		■	■	■			■			■		■	7
Features of the system's components		■			■	■	■			■	■	■		7
Explainability	■	■		■					■		■	■	■	7
Description of interactions		■		■			■			■	■	■	■	7
Performance		■	■		■				■					4
Adaptability	■			■							■			3
Presence of elements of discretization		■			■		■							3

Figure 2. Resulting categories to distinguish equation- and agent-based approaches. The column on the right contains the number of papers that mention each category (total number of papers considered for the review: 13).

Before going in details of all the criteria, we want to emphasize that they have not to be interpreted as universal, clear-cut criteria that can be applied to all equation- and agent-based models, regardless of the context. There are authors in the field of epistemology of simulations who say that it can be risky and unproductive to force distinctions when they are not needed or simply do not exist. Gräbner and colleagues (2019), whose paper was included in our review, question for example the very same terminology with which we use to distinguish *equation-based* models and *agent-based* ones: “from a technical perspective, ABMs always consist of equations. Due to the Church-Turing thesis, every computer program could equally be expressed as a recursive function and many ABM include equations explicitly” (Gräbner et al., 2019, p. 764). Following the authors, we argue that, given the complexity of the topics at stake, the continuous advances in simulation practice, and the variety of disciplinary fields involved, “a strictly dichotomous distinction is not helpful” (ibidem). That is why, reformulating the names of the criteria of comparison we tried to avoid counterposing opposite features that could be misleading. For example, instead of writing

"continuous vs discrete" we propose to use as a criterion of comparison "presence of elements of discretization"[11].
In the following paragraphs we analyse each criterion to point out the differences between equation- and agent-based approaches that are considered in the papers.

4.2.1 Computational intensiveness

The first criterion of comparison refers to the computational power and resources needed to simulate equation- and agent-based models.
For Hunter, Mac Namee and Kelleher (2018), "equation based models tend to be less computationally intensive than simulation models and are faster to run" while "agent-based models are computationally intensive and may take a long time to run to completion" (p. 2). This is because agent-based models are structurally built to capture local interactions, as we will discuss later, hence "tracking and scheduling a large number of interacting agents leads to serious computational requirements and analytical challenges" (Bobashev et al., 2007, p. 1532).
A related aspect concerns also the data availability that is a criterion that is often used to distinguish between the use of an approach or another (Bobashev et al., 2007).

4.2.2 Relationships between system's levels

Equation- and agent-based models can also be compared in terms of the way in which they focus on the microscopic and macroscopic levels of the system, and the relationship that appears between the two.
Equation-based models are said to focus on macroscopic regularities, to represent phenomena at the macro level, while agent-based ones are positioned at an individual, microscopic level (Duan et al., 2014). If the macroscopic patterns are explicitly modelled in the equation-based case, with agent-based approaches the aggregate structures are generated starting from interactions which are explicitly modelled only at local level (Bobashev et al., 2007). We recall that macroscopic and microscopic levels only indicate the perspective taken by the modeller on the phenomena, and do not refer to any specific, pre-determined spatial scale (Marilleu, Lang & Giraudoux, 2018).
Some authors interpret this criterion as a crucial difference in the type of knowledge that the modeller imposes on the system. In case of the equation-based model, the modeller "begins with a set of equations that express relationships among observables" and "may recognize that these relationships result from the interlocking behaviors of the individuals, but those behaviors have no explicit representation". On the opposite, the agent-based modeller "pays close attention to the observables as the model runs, and may value a parsimonious account of the relations among those observables, but such an account is the result of the modeling and simulation activity, not its starting point. The modeler begins by representing the behaviors of each individual, then turns them loose

[11] We thank Prof. Danny Caballero who reviewed this dissertation and suggested the criticalities of the previous "dichotomous presentation".

to interact. Direct relationships among the observables are an output of the process, not its input" (Van Dyke Parunak, Savit & Riolo, 1998, p. 19). Hence, describing the evolution and relationship among macroscopic observables is the purpose of the equation-based models but it would be incorrect to say that this macroscopic level is absent in case of the agent-based approaches: "system-level observables does emerge from an agent-based model, but the modeler is not as likely use these observables explicitly to drive the model's dynamics as in equation-based modelling" (Van Dyke Parunak, Savit & Riolo, 1998, p. 20).

Following this distinction on the modeller's knowledge about macroscopic observables or microscopic interactions, it is also very frequent to describe equation-based models as top-down and agent-based ones as bottom-up: "Agent based model also using an approach of bottom-up modeling because the basic thing need to be done is to identify the characteristic of the agents as well as the interaction that occurs among the agents" (Sumari et al., 2013).

A further aspect connected to the levels of the system is emphasized by Gräbner and colleagues (2019) reporting a work by Rust (1998) on the centralization versus distributed computation of the models: "in ABMs model dynamics are the result of the distributed computations of the agents, while in EBMs they are the result of the centralized computation of a set of equations" (Gräbner et al., 2019, p. 769).

4.2.3 Probabilistic nature

The third more frequent criterion of comparison that emerges from our review regards the probabilistic character of equation- and agent-based models.

When comparing the two about probability, the first distinction is that equation-based models are deterministic while agent-based ones are stochastic: "as ABMs are designed to be stochastic, each model run produces a different result. The equation based model is non stochastic" (Hunter, Mac Namee & Kelleher, 2018, p. 8); "we contrast the dynamics of a stochastic AB model with those of the analogous deterministic compartment DE mode. Obviously, deterministic models yield a single trajectory for each parameter set, while stochastic models yield a distribution of outcomes" (Rahmandad & Sterman, 2008, p. 998).

Following from this basic distinction, other authors elaborate more on the reasons behind the stochasticity of agent-based models and its absence in equation-based ones: "EBMs are usually very exact in the process of model exploration. This is because all mechanisms are expressed via clear equations and verification can take the form of a rigorous proof. ABMs, on the other hand, usually are not amendable to proofs and must be simulated. But a single simulation only represents one potential trajectory through the state space of the model and even more elaborate statistical analysis of the results does not offer the certainty of a mathematical proof" (Gräbner et al., 2019, p. 768). For Gräbner and colleagues, equation-based models are compared to the "certainty of a mathematical proof", which is "rigorous" and "very exact". On the other side, agent-based models are said to be "not amendable to proofs" and for this reason they need a computational method i.e., the simulation, to be explored.

Bruch and Atwell (2013) analyze the sources of uncertainty in agent-based models: input uncertainty and model uncertainty. “Input uncertainty - also known as epistemic uncertainty - arises due to incomplete knowledge of model input parameters; for example, the parameter estimates from a behavioral model estimated from survey data will represent point estimates with associated standard errors. Alternatively, the data used to initialize the model may have some uncertainty due to sampling variability. Model uncertainty arises because the model typically requires some set of unverifiable assumptions about key parameters, processes, or social interactions. Thus, this source of uncertainty is associated with the architecture of the model. Model uncertainty and input uncertainty imply that there are a number of alternative specifications of the model possible, and these alternatives may generate variability in the outcome of interest […] Agent-based models also have a third source of variability due to the stochastic elements of the model. Stochastic variability refers to the variation in model estimates that occurs from randomness within the model. For example, if agents’ choices are realized from probabilities, there will be fluctuation from model run to model run due to random sampling” (Bruch & Atwell, 2013, p. 14).

4.2.4 Features of the system’s components

The two approaches to modelling and simulation can also be compared in terms of how they represent the components of the system. About this, the main criterion found in the literature regards the homogeneity and heterogeneity of components. Focusing on the macroscopic level of the system, equation-based models consider the target system as an undifferentiated whole. “Whereas DE models assume homogeneity and perfect mixing within compartments, AB models can capture heterogeneity across individuals and in the network of interactions among them” (Grune-Yanoff & Weirich, 2010). Hunter, Mac Namee and Kelleher detail more about equation-based homogeneity and agent-based heterogeneity looking at the specific case of epidemiological modelling: “equation based models are designed for a homogeneous population and each additional characteristic added to the population, such as age, vaccination status or socioeconomic status requires additional equations to be added into the model, making the model more complicated and harder to solve and analyse. In addition, equation based models assume homogeneous mixing, each agent has an equal probability of coming into contact with every other agent. [...] One of the main advantages of modelling at the agent level is the ability to create heterogeneous agents. Each agent can have a list of their own characteristics such as age, gender or vaccination status and theoretically each agent could be unique with a different combination of characteristics. These characteristics can affect the agents’ likelihood to con- tract a disease directly or by influencing the agents’ decisions and thus who they come into contact with. Because agent-based models allow the agents to make decisions and move throughout the environment the agents in an agent-based model have realistic heterogeneous contact patterns” (Hunter, Mac Namee & Kelleher, 2018, p. 2).

4.2.5 Explainability

A further level of comparison between equation- and agent-based approaches regards the models' interpretability. We name this criterion "explainability" since it echoes important debates in the field of education (see Chapter 2 of this dissertation for further details, or section 2.4 of the current chapter).

Agent-based models are said to be more explainable because, at the stage of model's validation, the mechanisms at its basis can be inspected explicitly: "the ABM has increased the explanatory meaning of the associated EBM" (Gräbner et al., 2019, p. 768) and "ABMs have more potential for validation and are well suited for what we call mechanism-based explanations" (p. 771).

The detail of representation of the interactions impacts the explanatory power of the two kinds of models. Indeed, an important requirement for explainability is the verisimilitude and resemblance to real phenomena. As pointed out by Van Dyke Parunak, Savit and Riolo (1998), "ABM's give more realistic results than EBM's, for manageable levels of representational detail. The qualification about level of detail is important. Since PDE's are computationally complete, one can in principle construct a set of PDE's that completely mimics the behavior of any ABM, and thus produce the same results. However, the PDE model may be much too complex for reasonable manipulation and comprehension. EBM's (like system dynamics) based on simpler formalisms than PDE's may yield less realistic results regardless of the level of detail in the representation" (p. 23). The verisimilitude of the results offered by agent-based models is an important aspect also for Hunter, Mac Namee and Kelleher (2018) who focus on the possibilities of understanding of the global evolution of an epidemic spread phenomenon: "with the ABM results we are better able to understand how the vaccination policy might influence an outbreak in the real world. It is highly unlikely that a real outbreak will match the equation based model results exactly. It is much more likely that a real outbreak will fall into the range of our ABM results" (Hunter, Mac Namee & Kelleher, 2018, p. 8).

4.2.6 Description of interactions

Linked to the different level of granularity of the system's description according to the two approaches, another criterion of distinction concerns how interactions are modelled.

Several authors emphasize the complexity of interactions represented in agent-based models. Agents interact at the microscopic level and exchange different types of information – the nature of which strictly depends on the specific model at stake (Bobashev et al., 2007).

Some mechanisms of interaction are also intrinsically very difficult to represent in an equation-based models, while agent-based ones can easily do it without suffering from issues of system's tractability: "due to tractability considerations, EBMs have fewer dimensions than ABMs. That is, EBMs require a greater reduction of complexity and include fewer variables than ABMs. This means that the ability of EBMs to represent reality is more restricted, and that they can be explored in fewer dimensions than ABMs. In particular, there are certain mechanisms that are very difficult to represent in an EBM" (Gräbner et al., 2019, p. 768).

Moreover, the interactions in agent-based models occur at local level according to different metrics of vicinity that can depend on spatial closeness or network structures that are usually absent in equation-based descriptions (Sun & Cheng, 2005).

4.2.7 Performance

The criterion of performance includes a variety of meanings that the papers that we selected considered to distinguish agent- and equation-based models. We summarized all of them in a single category, given the fact that all relate to the efficacy of the model with respect to specific metrics or goals.
The first shade of the performance criterion is point out by Sun and Cheng (2005) who distinguish the most appropriate domains in which equation- and agent-based models can be successfully applied: "for equation-based modelling, the most appropriate domains are systems that can be modelled centrally, and in which the dynamics are dominated by physical laws; for agent-based modelling, the most appropriate domains are systems with high degree of localization and distribution, dominated by discrete equations" (Sun & Cheng, 2005, p. 7).
Strictly connected with the domains of reference, the second issue regards the practical use that we want to do of the two models. Sukumar and Nutaro (2012) point out that equation-based models are mainly used for evaluation of what-if scenarios while agent-based models for observing patterns of emerging behavior. When it comes to the specific use of these models in support of decision-making processes, the same authors say that equation-based models mainly contribute to decisions in operation, while agent-based models in planning.
The performance of models does not concern only their use in different fields or for different scopes but can regard more specifically the models' response to some techniques or metrics. For Kennedy and colleagues (2006), agent- and equation-based models perform differently with standard model testing. Rahmandad and Sterman (2008), focusing on the case of epidemiological models, point out that the two approaches "differ for several metrics relevant to public health, including diffusion speed, peak load on health services infrastructure, and total disease burden" (p. 998).

4.2.8 Adaptability

Another criterion to compare equation- and agent-based approaches regards their adaptability to changes. Agent-based models are usually more flexible and adaptable then the equation-based counterparts. Hunter, Mac Namee and Kelleher (2018) exemplify this in the case of epidemiological modelling: "It should be noted, however, that one of the advantages of the ABM comes in its adaptability. In order to add push vaccinations or change contact patterns the same ABM could be used just with different parameters while a new equation based model would need to be created" (p. 10).

4.2.9 Presence of elements of discretization

The last criterion of comparison identified in the literature review was the presence, in the two different approaches to modelling, of elements of discretization. Specifically, two forms of discretization have been identified. The first regards time, the second concerns the components of the systems e.g., individual agents. Equation-based models are continuous both in time and in the way they model the system as an undifferentiated whole (Grüne-Yanoff & Weirich, 2010; Rahmandad & Sterman, 2008). On the opposite, agent-based approaches have a discrete representation of time (Sun & Cheng, 2005; Sukumar & Nutaro, 2012) and are discrete by nature since the minimal element considered is the agent, which is the individual component of the system.

4.3. Selection of the analytical lenses from the criteria of comparison

From the review we obtained a list of nine criteria that are used in the literature to distinguish between equation- and agent-based approaches to modelling and simulation. We realized that, for the purposes of the work we were meant to do in this chapter, we did not need all these criteria for our educational reconstruction of the SIR models and simulations.

We did not consider: i) the computational intensiveness, since the SIR model was kept both in the equation- and in agent-based form as simple as in the formulation by Kermack and McKendrick, hence the distinction between the computational resources would not be huge enough to deserve attention; ii) the features of the system's components, since the agent-based model discussed is equivalent to the equation-based one, without any further heterogeneity in terms of age, vaccination state, or routine of social interaction; iii) the explainability, for the reasons already mentioned that are connected to the simplicity of the model considered; iv) the description of interactions, because partially this criterion has been included in the probability-related one; v) the performance, since we do not need to test the two models against specific metrics; vi) the adaptability, because, as already commented, the assumptions at the basis of the two types of models are the same and the agent-based model does not introduce further element of complexity.

Of the nine criteria retrieved from the literature, three were selected as the *lenses* to analyse the SIR model, to orient the presentation of the contents, and to compare in particular equation- and agent-based approaches to their simulation. They are:

- Lens 1) Relationship between system's levels
- Lens 2) Probabilistic nature
- Lens 3) Presence of elements of discretization

In Table 5 we summarize the main differences between the two approaches with respect to the three criteria. These criteria will be used in Section 7 as lenses to examine the comparison between equation- and agent-based approaches in a specific case study: the SIR model for the spread of a virus in a population.

Table 5. Comparison between equation- and agent-based simulations in terms of three analytical lenses selected from the literature review.

	Equation-based simulations	Agent-based simulations
Lens 1 Relationship between system's levels	The equations do not emphasize the microscopic entities explicitly but estimate the behavior at the macroscopic level.	The local interactions among the agents lead to emergent phenomena observed by the macroscopic behaviors at the aggregate level.
Lens 2 Probabilistic nature	The equations are deterministic: from the present state, the numerical methods used by the simulation lead to the future state of the target system in a univocal and pre-determined way.	The system is modelled as divided in its discrete minimum components, i.e. the agents, which are a finite number in $\mathbb{N}$. Time is also a finite sequence of discrete time steps.
Lens 3 Presence of elements of discretization	The system is modelled as an undifferentiated whole and the differential equations are continuous both with regard to population and time which vary in $\mathbb{R}$. The discretization follows for solution purposes through numerical methods.	The system is modelled as divided in its discrete minimum components, i.e. the agents, which are a finite number in $\mathbb{N}$. Time is also a finite sequence of discrete time steps.

5. The SIR model for the spread of diseases

Mathematical studies on the development of epidemics date back to XVIII century, with the studies by Daniel Bernoulli who developed a model for smallpox (Hethcote, 2000). However, the mathematical theory of epidemics we base on nowadays was born in the 20th century, in 1927, when mathematicians William Ogilvy Kermack and Anderson Gray McKendrick published their SIR model (Kermack & McKendrick, 1927). The basic idea of the authors was to study the spread of a disease in a population by dividing it in compartments, that are mutually exclusive classes to which individuals of the population belong. Three compartments are considered in Kermack and McKendrick's model:

- S: susceptible: healthy individuals that can be infected and can contract the disease;
- I: infectious: individuals that have contracted the disease and can infect others;
- R: removed: individuals that have recovered from the disease and have been immunized (they are not susceptible anymore), or that have died due to the disease;

The model was named SIR due to the initial letters of the three compartments.
The temporal evolution of the three compartments is described by a set of three ordinary non-linear differential equations (ODEs):

$$\frac{dS(t)}{dt} = -\frac{\beta I(t)S(t)}{N} \quad (1)$$

$$\frac{dI(t)}{dt} = \frac{\beta I(t)S(t)}{N} - \gamma I(t) \quad (2)$$

$$\frac{dR(t)}{dt} = \gamma I(t) \quad (3)$$

where β is the infection rate, γ the recovery-or-death rate and N the total population size, while $S(t)$, $I(t)$ and $R(t)$ respectively represent the sizes of the susceptible, infectious, and removed compartments over time.
The ODEs in (1-3) express the variation in time of the classes of susceptible, infectious, and removed under the assumption that the sum of the three compartments remain constant during the evolution of the model and equals the size of the population (4). Hence, the sum of the derivatives must equal 0 (5):

$$S(t) + I(t) + R(t) = N = cost \qquad (4)$$

$$\frac{dS}{dt} + \frac{dI}{dt} + \frac{dR}{dt} = 0 \qquad (5)$$

A possible way to represent the dynamics of the system embedded in the equations is through a flow diagram, reported in Figure 3. In the three blocks we have the three compartments of the model (susceptible, infectious, and removed) and over the arrows the transition rates from one compartment to the other are indicated.

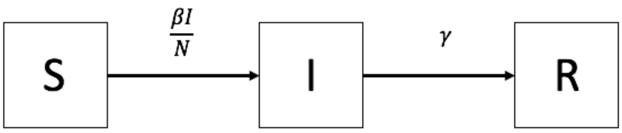

Figure 3. Flow diagram representation of the differential equations of the SIR model.

5.1. Making sense of the model

We can expect that the number of susceptible individuals to an epidemic decreases over time and this explains the minus sign for the derivative. Moreover, the variation of S compartment depends on the number of susceptible individuals at a certain time, multiplied by the rate of infection for a susceptible individual (β). Indeed, this rate multiplied the number of susceptible give the number of individuals that have to be removed from the S population. The composition of these terms returns the equation (1) for dS/dt.
All the individuals which are removed from S compartment become part of the I compartment, hence there is the same term, opposite sign, in the equation (2) for dI/dt. Moreover, the I compartment has to take into account a reduction due to the people that recover from the disease or die because of the disease (expressed through the recovery-or-death rate γ), hence are removed from the infectious compartment.
The compartment for recovered individuals always increase over time and this explains the positive value of the derivative in the equation (3) for dR/dt. In particular, the R compartment increases whenever individuals are removed from the I compartment, with the recovery-or-death rate γ.

5.2. Output of the model

The results of the application of the SIR model are usually represented in a graph like that in Figure 4 where the evolutions of the susceptible, infectious, and removed compartments are reported.

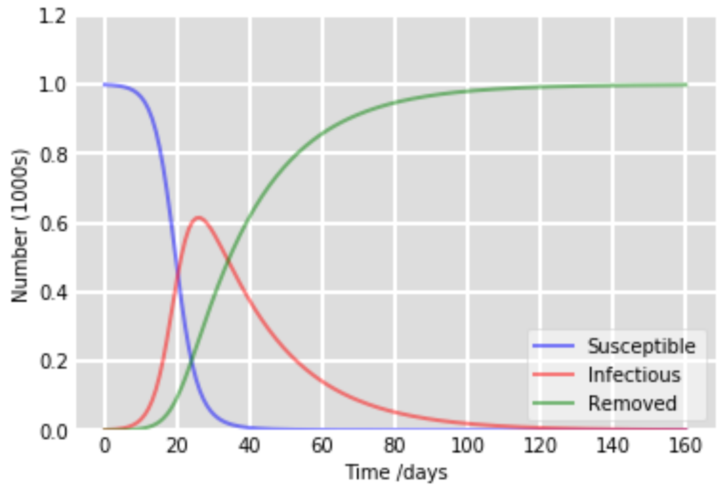

Figure 4. Evolution of susceptible, infected, and removed compartments over time.

The number of susceptible individuals always diminishes, while the number of removed always increases. The infected curve is bell-shaped. Indeed, at the beginning of the epidemics, the susceptible number decreases due to the infections, and the infected number increases because susceptible individuals become infected. Then, as the infected number increases, it is more probable that a susceptible individual becomes infected. As a consequence, at the beginning the infected curve grows, but at a certain moment some infected individuals will start recover or will die, so they will become part of the removed compartment, and that is why the curve of removed grow, letting the curve of infected diminish.

5.3. Assumptions of the model

The SIR model is based on many assumptions:

- A1. The population is isolated: no one enters, and no one leaves
- A2. The epidemic occurs in a short time compared to the vital dynamics: births and deaths (not due to the disease) are neglected
- A3. The only way a person can leave the susceptible group is to become infected
- A4. The only way a person can leave the infected group is to recover from the disease or to die
- A5. Once a person has recovered, the person received immunity and can no longer become infected
- A6. Age, sex, social status, and race do not affect the probability of infect and being infected
- A7. There is no inherited immunity

A8. The members of the population mix homogeneously, i.e. they have the same interactions with one another to the same degree

A9. The disease has no incubation period

These are strong assumptions that make the equations of the model so simple. In a real case like the COVID-19 pandemic most of these assumptions cannot be held true. For example, deaths for other causes than the disease under study must be considered (A2), because people die also without getting infected (A3). About the supposed immunity received after the infection, on April 24, 2020, the World Health Organization wrote that "[t]here is currently no evidence that people who have recovered from COVID-19 and have antibodies are protected from a second infection" (WHO, 2020) (A5). Moreover, the measures of social distancing, confinement and quarantine for infected people have made the hypothesis of homogeneous mixing unrealistic (Anand, Sabarinath, Geetha & Somanath, 2020) (A8). Even the assumption on the incubation period cannot be held true; indeed, it has been estimated that "the median incubation period for COVID-19 is 5.1 days and 97.5% of those who develop symptoms do so within 11.5 days of infection" (Lauer et al., 2020) (A9).

In the last century, many different versions of this model have been produced to adapt it to different epidemiological contexts. Other compartments have been added to the three canonical. For example, the SIRD models splits the removed compartment in two: recovered (R) and deceased (D). In the MSIR model, M class for individuals with maternally derived immunity is added. The SEIR model includes the exposed (E) compartment to consider the existence of a non-zero incubation period during which the individuals have been infected but are not infectious themselves. Also during the COVID-19 pandemic, a lot of studies have been developed, for example customizing the SIR model on the various national and regional constraints and needs (Reno et al., 2020). However, the core idea of all these models, that is the separation of population compartments and description of their evolution with differential equations, has remained that of Kermack and McKendrick.

6. Computational models and simulations for the SIR model

In the previous section we have presented the SIR model for the spread of an infectious disease, its output, and assumptions. Recalling the definition by Paul Humphreys discussed in section 2.2, we have so far limited ourselves to present the model B formulated for a real system R. More explicitly, the model is the SIR by Kermack and McKedrick, developed to interpret, explain, and predict the real phenomenon of the spread of a disease in a population. In this section, we aim to present the other two layers of Humpreys' definition, that are the computational model (C) and the simulation (S) for the SIR model (B). In particular, we will discuss two approaches to computational modelling and simulation, already introduced in section 2.3: the equation- and agent-based approaches. After having presented them, we draw a comparison in terms of the epistemological issues they raise. In this section, we provide details on the different computational models, on their implementation in Python and NetLogo languages and on the results of their execution through simulation. The technicalities that could interest some readers are collected in tables and can be overlooked by others. Indeed, the crucial points relevant for the argumentation are discussed from a conceptual and epistemological point of view in the body of the text and for their understanding no technical knowledge is required.

6.1. Equation-based approach to computational modelling and simulation

The SIR model is usually addressed as one of the main examples of equation-based models because it is already expressed as a system of differential equations (1-3). We present two computational equation-based models, and the results of their simulations.

6.1.1 Numerical integration method via odeint

The first approach consists in the numerical integration of the system of equations (1-3). All integration methods have three elements in common. The first, which is rather obvious, is a function that expresses the equations that one wants to integrate; we have already presented and discussed them extensively in section 4. The second requirement is the statement of initial conditions, in this case the values for the population of S, I and R compartments. In particular, we assume that at the beginning of the epidemic, the S compartment includes all the population but one individual, which is infectious, and that the R compartment is empty. In formulas:

$$S(0) = N - 1 \qquad (6)$$

$$I(0) = 1 \qquad (7)$$

$$R(0) = 0 \qquad (8)$$

The third element which is essential for all the methods that solve initial value problems is the creation of a monotonically increasing sequence of discrete time values.
The computational model based on numerical integration is expressed in Table 6, with a description of the algorithm alongside an implementation in Python language, using the "odeint" function[12].

Table 6. Equation-based computational model with numerical integration method through odeint (description of the algorithm and implementation in Python language).

	Description of the algorithm	Python code
1	Import needed tools from existing libraries: 7. multiplication operator 8. module for numerical integration	`from numpy import *` `from scipy import integrate`
2	Initialize variables:	`beta = 0.8`

[12] The computational model presented in the followings makes use of the odeint function, which in turn implements the lsoda algorithm for initial value problems (Hindmarsh, 1983; Petzold, 1983). The main characteristic of the lsoda method is that it automatically switches between stiff and non-stiff method without the user determines whether the problem is stiff or not. We recall that a stiff differential equation is an equation for which certain numerical methods for solving it are numerically unstable, unless the step size is taken to be extremely small.

	9. rate of infection (beta) 10. rate of removing (gamma) 11. size of the population (N)	`gamma = 0.3` `N = 1000`

3	Define a function (dSIR_dt) that returns a three-components array for the variation of S, I and R compartments as expressed by the ODEs in (1-3). In particular, the first component is the right member of equation (1), the second is the right member of (2) and the third is the right member of (3).	`def dSIR_dt(SIR, t=0):`
		`    return array([ - beta*SIR[0]*SIR[1]/N ,`
		`                    beta*SIR[0]*SIR[1]/N`
		`                      - gamma*SIR[1] ,`
		`                    gamma*SIR[1] ])`

4	Define a vector (t) of evenly spaced numbers [0, 1, …, 50] to represent time.	`t = linspace(0, 50, 51)`
5	Define an array (SIR0) for the initial conditions of the size of the three compartments. Assume that at the beginning S compartment includes all the population but one individual (S(0) = N-1), which is infectious (I(0) = 1), and there are no removed (R(0) = 0).	`SIR0 = array([N-1, 1, 0])`
6	Compute the numerical solution for the system of ODEs written in dSIR_dt, under the initial conditions SIR0 on a sequence of time points t.	`SIR = integrate.odeint(dSIR_dt, SIR0, t)`
7	Store the values of susceptible, infectious and removed computed for each of the 51 time steps (optional, for visualization purposes only)	`susceptibles, infectious, recovered = SIR.t`

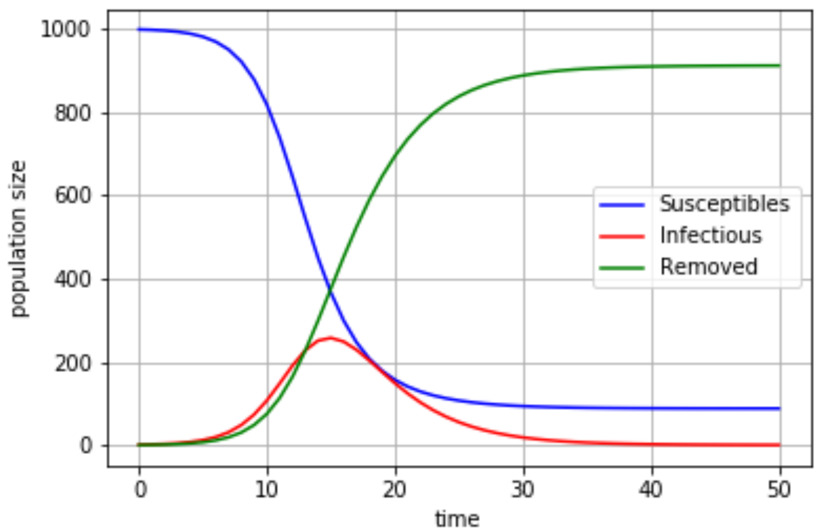

Figure 5. Results of the simulation of the computational equation-based model with odeint integration method: in blue the evolution of susceptible population size, in red the infectious, in green the removed ($\beta = 0.8, \gamma = 0.3, N = 1000, S(0) = 999, I(0) = 1, R(0) = 0, time = [0, 1, \ldots, 50]$).

We recognize the equation-based character of this computational model. The only elements expressed are:

1. the variation over time of the S, I and R populations, according to the mathematical model defined in equations (1-3) (step 3 in Table 6);
2. a sequence of time steps (step 4 in Table 6)

3. the initial conditions for the population size of the three compartments as expressed in equations (6-8) (step 5 in Table 6).

There is no reference at the individual components of the population and only measures about the size of three compartments are collected (step 7 in Table 6).

When the computational model is executed, we obtain a simulation, whose results can be visualized by plotting the graphs for the size of the three compartments over the 51 defined time steps. The result is reported in Figure 5.

6.1.2. Finite-difference method

Another equation-based simulation can be obtained with a slightly different computational model. It consists in making transparent the procedure of integration, previously embedded in the odeint function, using a finite-difference approach instead of the lsoda algorithm. Before presenting the computational model, we need to modify the mathematical SIR model presented in section 4. In particular, we make use of a truncated Taylor's series expansion. For a generic function $F(t)$ we have:

$$F(a+h) = F(a) + F'(a)h + R_i(t) \qquad (9)$$

Dividing across by h, we obtain:

$$\frac{F(a+h)}{h} = \frac{F(a)}{h} + F'(a) + \frac{R_1(t)}{h} \qquad (10)$$

which, when $R_1(t)$ is sufficiently small, gives the approximation of the first derivative of F:

$$F'(a) \approx \frac{F(a+h)-F(a)}{h} \qquad (11)$$

and the approximate value for the function in $t_0 + h$:

$$F(a+h) \approx F(a) + F'(a)h \qquad (12)$$

When applied to the SIR system of equations (1-3), and defined $h = 1$ to take into account the unit time step, the finite-difference approximation results:

$$S_{t+1} = S_t + \frac{dS}{dt} = S_t - \frac{\beta S_t I_t}{N} \qquad (13)$$

$$I_{t+1} = I_t + \frac{dI}{dt} = I_t + \frac{\beta I_t S_t}{N} - \gamma I_t \qquad (14)$$

$$R_{t+1} = R_t + \frac{dR}{dt} = R_t + \gamma I_t \qquad (15)$$

In this way, referring to the susceptible compartment (but the same considerations hold for the other two groups), the first computation takes as input the initial condition $S(0)$ and produces the result $S(1)$. Then, this value $S(1)$ is the input for the second computation which produces $S(2)$, that in turn becomes the input for the third computation. This iterative process can be visualized in the diagram in Figure 6.

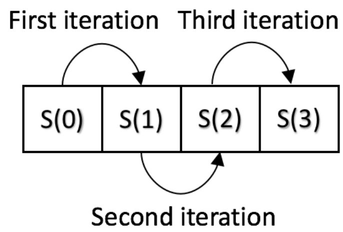

Figure 6. Iterative process of computation following the finite-difference integration method.

On the basis of the three equations above that constitute the revised mathematical model, we can implement a computational model. We report it in Table 7.

Table 7. Equation-based computational model with finite difference integration method (description of the algorithm and implementation in Python language).

	Description of the algorithm	Python code
1	Import needed tools from existing libraries: 4. multiplication operator	`from numpy import *`

2	Initialize variables:
	5. rate of infection (beta)
	6. rate of removing (gamma)
	7. size of the population (N)
		`beta = 0.8`
		`gamma = 0.3`
		`N = 1000`

3	Initialize three lists with initial conditions (the initial size of three compartments).	`S = [N-1]`
		`I = [1]`
		`R = [0]`

4	Define a function (population_t1) that implements the computation expressed in (13-15). In particular it takes the last element of the S, I, R lists (named S_t0, I_t0, R_t0) and computes the values S_t1, I_t1, R_t1. Finally, it adds these values as lasts elements of the S, I, R lists and returns the updated lists.	`def population_t1():`
		`    S_t0 = S[-1]`
		`    I_t0 = I[-1]`
		`    R_t0 = R[-1]`
		`    S_t1 = S_t0 - beta*I_t0*S_t0/N`
		`    I_t1 = I_t0 + beta*I_t0*S_t0/N - gamma*I_t0`
		`    R_t1 = R_t0 + gamma*I_t0`
		`    S.append(S_t1)`
		`    I.append(I_t1)`
		`    R.append(R_t1)`
		`    return S, I, R`

5	Execute the population_t1 function 50 times, obtaining 50 computed values + the initial conditions.	`for i in range(49):` `    population_t1()`

When the computational model is executed, the results of the simulation can be visualized by plotting the values of the components of S, I and R vectors. The plot is reported in Figure 7.

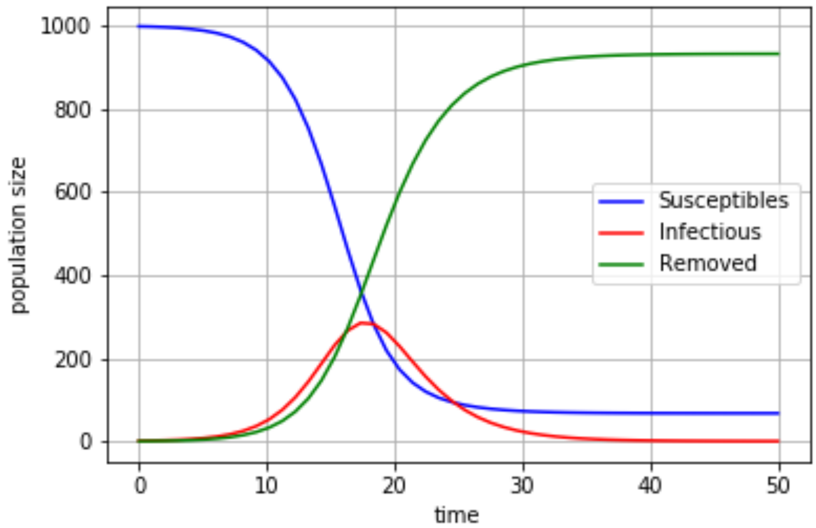

Figure 7. Results of the simulation of the computational equation-based model with finite difference integration method: in blue the evolution of susceptible population size, in red the infectious, in green the removed ($\beta = 0.8, \gamma = 0.3, N = 1000, S(0) = 999, I(0) = 1, R(0) = 0,$ $time = [0, 1, \ldots, 50]$).

6.1.3. Comparison of two numerical integration methods

Both the integration presented through the odeint method and the finite-difference approaches are equation-based. The only information provided and extracted from the models are the size of the S, I, and R compartments, and their variation over time. The individuals which are part of the compartments are not traceable, because the models focus on the compartments as a whole, not on their constituents.

However, despite the similarities due to their equation-based character, the two approaches also present differences. The numerical methods used for the two simulations are different and lead to similar but not exactly equivalent results, even when the same values for parameters and initial conditions are considered. In Figure 8, the results of the odeint and finite difference simulations are visually compared.

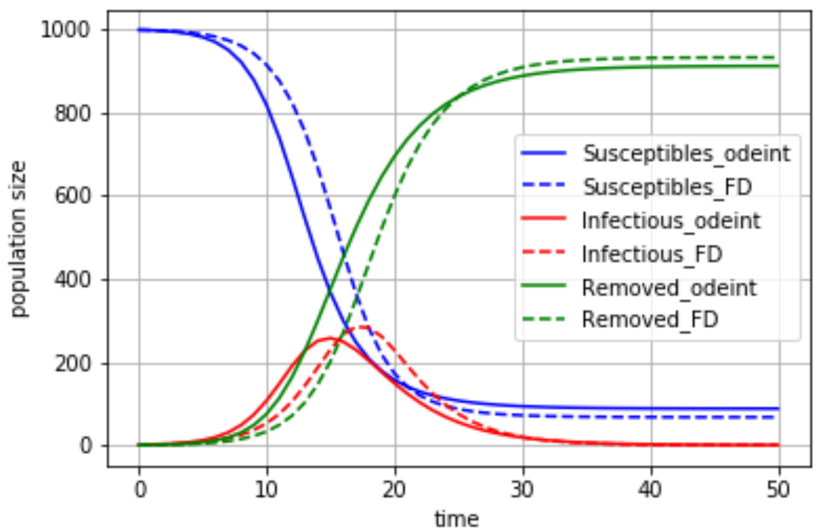

Figure 8. Comparison of the evolution of the compartments with the two equation-based methods: the results of the application of odeint method are reported in solid line style, those of finite difference method (FD) are in dashed line style; in blue the evolution of susceptible population size, in red the infectious, in green the removed ($\beta = 0.8, \gamma = 0.3, N = 1000, S(0) = 999, I(0) = 1, R(0) = 0, time = [0, 1, \dots, 50]$).

The shapes of the curves are similar, but the finite-difference method seems lead to a "delay" with respect to the odeint method. In papers that discuss the comparison between integration methods applied to the SIR model, the same results are obtained but the reasons behind this difference are not explained (Macal, 2011). Here we take this evidence to further stress that the difference in the output strongly depends on the mathematical and computational formulation of the specific integration method. While we have explicitly addressed the finite difference method in (13-15), we did not dig deep into the details of the odeint method. Making transparent the complete process underlying the odeint method goes beyond the purposes of this chapter, but we want to highlight a difference between the two considered methods regarding the kind of discretization they operate on the SIR continuous model. Rather than characterizing the distinctions between the methods themselves from a technical point of view, we will consider which elements of discretization need to be *explicitly* inserted in the simulation by the users, and which appear only *inside* the run of a specific integration method[13].

In the case of the integration model via odeint, a system of differential equations is integrated through a numerical method. This method requires a discretization of time, which is provided in input by the programmer: in line 4 (Table 6), we defined a vector (t) of evenly spaced numbers that represented the time steps on which reporting the results of the lsoda algorithm[14]. With this method, the equations that the user needs to insert in the computational model in line 3 (Table 6) are in the same continuous form of those reported in (1-3) for the SIR model by Kermack and McKendrick. The discretization of the equations is not set explicitly by the user but happens when the odeint method runs.

In the case of finite difference method, we have something different. Here, the starting point is the reformulation of the mathematical model that makes an a priori discretization of the continuous SIR equations in (1-3) obtaining the ones in (13-15). Then, the computational model follows by implementing this mathematical model which is already suitable for numerical integration: we did this in line 4 (Table 7). Using a finite difference method, no further elements of time discretization are required, since the discrete character of time follows from the discrete character of the equations.

[13] The crucial distinction between the use of a certain method by the user and its inner functioning was made explicit after the comments of the reviewer, Prof. Danny Caballero.

[14] The time points in the vector (t) given in input are those set by the user to obtain the results i.e., a list of values for the population size of the three compartments S, I, and R. However, odeint uses internally adaptive time steps (not necessarily those indicated in t) and returns the values for S, I, and R for the time points specified in t by interpolation. This allows the odeint method to adapt to stiff equations that would give unstable solutions unless the time step is chosen small enough.

6.2. Agent-based approach to computational modelling and simulation

Until this point, we have examined only equation-based approaches to modelling and simulation of the spread of an infectious disease. A different approach to the spread of a disease is the agent-based one, which we will address in the current section.
Before presenting the computational model that we will use to realize the simulations, we need to reconsider the SIR model presented in section 5 and elaborate it from an agent-based perspective. We can start from the equation for the susceptible compartment:

$$\frac{dS}{dt} = -S\,P(susceptible\ becomes\ infectious) =$$
$$= -S\,P(susceptible\ contacts\ infectious)\,P(infectious\ infects\ susceptible) =$$
$$= -S\,[mean\ number\ of\ contacts\ for\ individual * P(the\ contact\ is\ infectious)] * \beta_i =$$
$$= -S\left[\beta_c \frac{I}{N}\right]\beta_i = -S\beta_i\beta_c\frac{I}{N} = -\frac{\beta IS}{N} \quad (16)$$

Following (Sterman, 2000; p. 302; Macal, 2011; p. 375), in the mathematical passages above we have interpreted the rate of infection β as the product of a number β_c that quantifies the mean number of contacts that each individual has (per unit of time) and of a number β_i that quantifies the probability for a susceptible individual of getting infected because of a contact with an infectious one. β_c is also called the "contact rate" and it is measured in people contacted per person per time period, while β_i is called the "infectivity". In this way, the probability that a susceptible becomes infectious ($P(susceptible\ becomes\ infectious)$) depends on the probability that a susceptible meets an infectious ($P(susceptible\ contacts\ infectious)$), and on the probability that a susceptible becomes infectious after the contact ($P(infectious\ infect\ susceptible)$). In turn, the probability that a susceptible meets an infectious depends on the mean number of contact that each individual has (β_c) and on the probability that the met individual is infectious ($\frac{I}{N}$). The composition of all the terms, given $\beta_i\beta_c = \beta$, returns the equation for dS/dt in (1).
Similar considerations can be done for the equation for the removed compartment:

$$\frac{dR}{dt} = IP(infectious\ is\ removed) = \gamma I = \frac{1}{d}I \quad (17)$$

Here, the recovery-or-death rate γ can be modelled as the reciprocal of the average duration of infectivity d. This is also equivalent to the assumption that the duration of time spent by an individual in the infectious state is a random variable with an exponential distribution (Sterman, 2000; p. 305).
For deriving the infectious compartment, we can apply the boundary condition 5:

$$\frac{dI}{dt} = -\frac{dS}{dt} - \frac{dR}{dt} = \frac{\beta IS}{N} - \gamma I = \frac{\beta IS}{N} - \frac{1}{d}I \quad (18)$$

The mathematical model obtained above is formally equivalent to the SIR classical model presented and discussed in section 4. We have only substituted parameters with other combination of parameters, but the form of the equations has remained the same. The novel element, which is relevant for the argumentation that follows, is in the interpretation of the variables in the equations. While in (1-3) we had rates of infection and recovery-or-death, in (16-18) we are referring to contacts that individuals of different compartments have, to probability that a single susceptible individual is infected after a contact with an infectious individual, to average duration of infectivity. The novelty, in a nutshell, is that in the new formulation we refer to the individual components of the population: the *agents*.

With this mathematical adaptation in agent-based perspective of the SIR model, we can introduce the features of the computational model at the basis of the simulation. A generic agent-based model consists in creating a given number of agents, which are the individual elements of the model. Then, to this agent are associated variables and rules. The former are chosen to represent the agent's status throughout the evolution of the system. The latter describe the allowed behaviour of the agent with respect to the other agents and the environment. In addition to these basic elements, the agent-based model usually defines and provides measures on the ensemble of agents; this can be particularly useful to compare the results of the agent-based model with the equation-based ones.

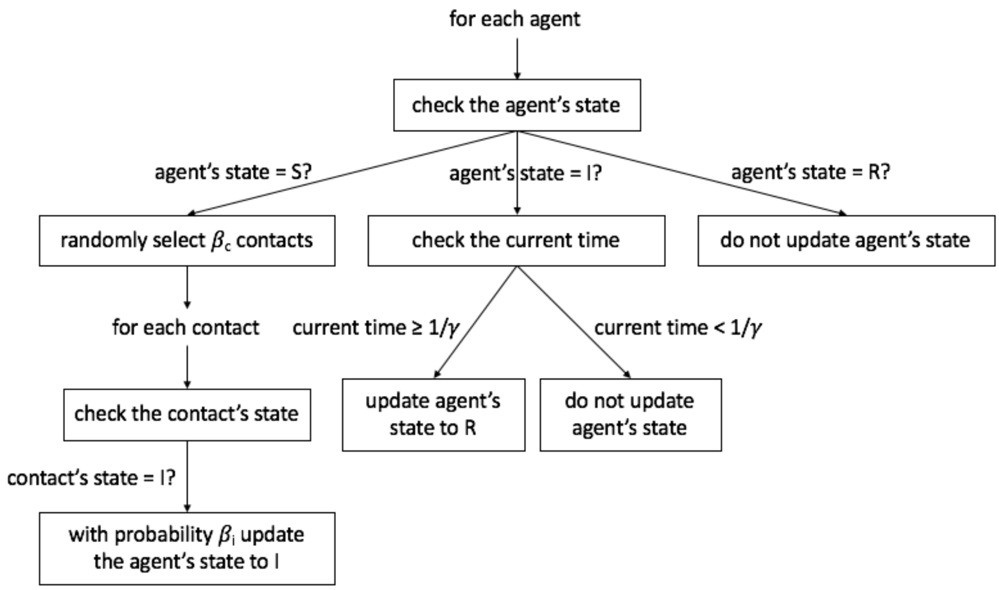

Figure 9. Diagram representation of the rules associated to each agent of the model (adapted from Macal, 2011).

In the case of the SIR model, these generic steps can be translated into an algorithm, or collection of procedures, that constitutes the computational agent-based model for the spread of a virus. Firstly, we must create as many agents as the size of the population previously considered. The variables to be associated to the agents describe their status of susceptible, infectious, or removed; moreover, each agent must have its own "clock"-variable to measure the time of potential infection

and the duration of infectivity. The rules that the agents must follow are summarized in the diagram in Figure 9. From the diagram, we can notice a substantial difference with respect to the case of equation-based models. In those cases, presented in section 6.1, every compartment varied along time, while here only susceptible and infectious agents have associated rules, because the removed just remain in that state.
The last component of the agent-based SIR model is optional and consists in defining cumulative variables that at each time step count the number of agents with S, I and R state. On the basis of the adapted SIR model and on the rules described in Figure 9, we can implement a computational agent-based model. We report it in Table 8.

Table 8. Agent-based computational model (description of the algorithm and implementation in Python language).

<table>
<tr><th></th><th>Description of the algorithm</th><th>Python code</th></tr>
<tr><td>1</td><td>Import needed tools from existing libraries:
8. multiplication operator
9. module for generation of random numbers</td><td><pre>from numpy import *
import random</pre></td></tr>
<tr><td>2</td><td>Initialize variables:
10. contact rate (betac)
11. infectivity (betai)
12. rate of removing (gamma)
13. number of agents (N)</td><td><pre>betac = 1
betai = 0.8
gamma = 0.3
N = 1000</pre></td></tr>
<tr><td>3</td><td>Initialize a N-components list (L), each component with value ‘S’ to represent the agents' susceptible states.</td><td><pre>L = []
for i in range(N):
    L.append('S')</pre></td></tr>
<tr><td>4</td><td>Select a random element in the list L and substitute the ‘S’ value with the tuple (‘I’, 0): the first element of the tuple represents the agent’s state, the second one represents the infection time.</td><td><pre>rnd_temp = random.randint(0, N)
L[rnd_temp] = ('I', 0)</pre></td></tr>
<tr><td>5</td><td>Initialize three lists (S, I, R) containing as first elements respectively the number of susceptible, infectious, and removed agents in the list L.
Also initialize a counter for the number of tuples in the list L.</td><td><pre>S = [L.count('S')]
I = [L.count(('I',0))]
R = [L.count('R')]
num_tuple = 1</pre></td></tr>
<tr><td>6a</td><td>Create three indexes:
14. (tempo) to consider the 49 time steps at which we want to make the system evolve
15. (j) to scan over the N agents in L
16. (k) to scan the contacts of each agent
For each time step and for each agent:
17. if its state is ‘S’, randomly select a number of contacts depending on the contact rate: if the contact’s state is ‘I’, change the agent’s state to ‘I’ with probability betai (with a random number generation), store the information about</td><td><pre>for tempo in range(1, 50):
    for j in range(len(L)):
        if L[j] == 'S':
            for k in range(betac):
                rnd_temp = random.randint(0, N-1)
                if type(L[rnd_temp]) == tuple:
                    rnd_temp2 = random.random()
                    if rnd_temp2 <= betai:
                        L[j] = ('I', tempo)
                        num_tuple += 1
        if type(L[j]) == tuple:
            if tempo-L[j][1] >= 1/gamma:
                L[j] = 'R'</pre></td></tr>
</table>

	the time of infection in the tuple and increase the counter num_tuple by 1 18. if its state is 'I' (i.e. if its value is a tuple), and if the tempo index minus the time of infection is greater or equal to 1/gamma, change the agent's status to 'R' and decrease the counter num_tuple by 1	`num_tuple -= 1`

6b	For each time step, add to the S, I, R lists the number of susceptible, infectious, and removed elements in the L list (optional, for visualization purposes only)	`S.append(L.count('S'))`
		`I.append(num_tuple)`
		`R.append(L.count('R'))`

From the computational model we recognize its agent-based character. Detailed information is coded and provided for each of the individual agents: the list L contains the details for the state of all the N agents and, whether infectious, also the information for the infection time. At each moment of the simulated time, we can look at an element of the list and inspect the n-th agent we want to know the state. Aggregate measures for the number of agents in each state are possible (step 6b in Table 8) but not essential for the execution of the model. Another typical agent-based feature regards the rules associated to the agents. Their behaviour (i.e. their change of state) at a moment of simulated time is only determined by their state at that time and by the state of a selected contact agent.

When the computational model is executed, the results of the simulation can be visualized by plotting the values of the components of S, I and R lists. However, as we will discuss extensively in section 7, the presence of elements of randomization in the computational model (lines 4 and 6a in Table 8) leads to different results for each simulation. In Figure 10 we report the plot of the average results over 100 runs.

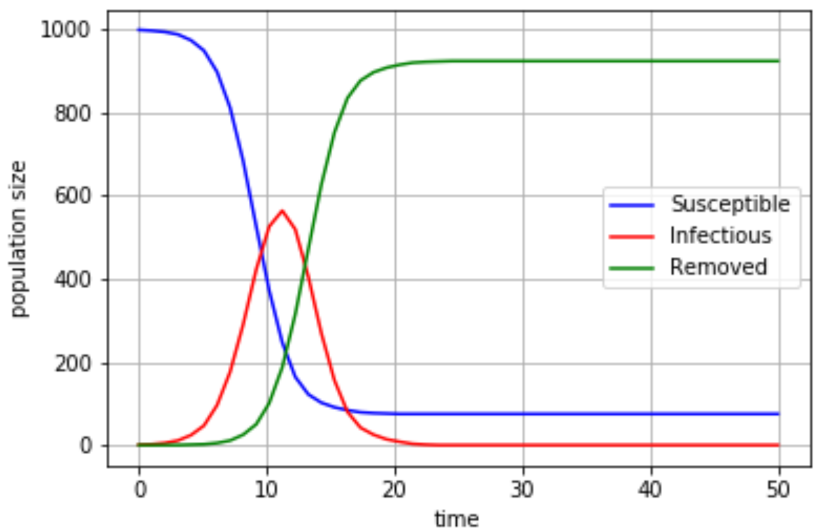

Figure 10. Average results of 100 simulation runs of the computational agent-based model: in blue the evolution of susceptible population size, in red the infectious, in green the removed ($\beta_i = 0.8$, $\beta_c = 1, \gamma = 0.3, N = 1000, S(0) = 999, I(0) = 1, R(0) = 0, time = [0, 1, \dots, 50]$).

The shapes of the curves are similar to those in Figures 5 and 7, and but there is a crucial difference. In both the equation-based approaches, the results of the simulations do not vary for different runs, while in the agent-based approach for each run a slightly different result is obtained. We will address this point in the next section about the comparison of the two approaches.

7. Comparison between equation- and agent-based approaches to SIR model

After having presented the equation- and agent-based approaches to simulating the SIR model, in this section we draw a comparison with the three analytical lenses derived and discussed in section 4.3 and highlighted in Table 5.

Lens 1: Relationship between system's levels
The equation-based model is top-down because the equations already include the expert knowledge on the problem. The agent-based model is bottom-up since the global behaviour of the population emerges from measures on the dynamics of the single agents and on its probabilities to become infected or recovered. The equation-based model examines the population as a whole, at most divided in compartments, while the agent-based model inspects each agent and provides details on its status.
The categories of comparison highlighted in this section are all elements that can describe not only the differences between equation- and agent-based simulations but also between classical and complex systems. Indeed, at the roots of complexity there is the presence in a system of a large but finite number of individual elements. Those elements, named agents, interact locally according to non-linear (sometimes probabilistic) relationships. In turn these rules, when applied to all the agents, give the system global emergent properties that can only partially be explained starting from the behaviour of individual components (Cilliers, 2002). The differences with classical systems are manifest. The linearity of interactions among components – which was a paradigm in Newtonian physics – ensures the superposition of effects on the system starting from the combination of the local behaviours ("the whole is the sum of its parts"). Classical systems are also deterministic since, given differential equations that describe their dynamics and initial conditions, their evolution over time is determined at any future state with arbitrary precision.

Lens 2: Probabilistic nature
From the results of the simulations, we have observed that the agent-based model produces different results each time it is executed, while this is not the case for the equation-based approach. One could suggest that in the agent-based approach there is a role for randomness which is neglectable in the equation-based one. However, also the equation-based approaches include information on the disease which relate to probability. For example, recalling the formulation of the SIR model in 1-3, the equations contain a probability for infection (β) and a probability of recovery-or-death (γ). However, these probabilities appear in the model only as rates, as frequencies that are parametrized in the model as constants. After having defined them, they become constant values, numerical parameters and lose their original meaning of probabilistic measures. On the opposite,

the agent-based approach genuinely includes in its formulation the stochasticity of the system, overcoming the determinism of differential equations. For example, recalling the formulation of the algorithm for the agent-based model, randomness appears explicitly twice: in the selection of contacts (β_c) and in the chance of getting infected after having contacted an infected agent β_i. In this case, when agents – not aggregate populations – are considered, every individual has a probability which is specified by the given parameters.

Lens 3: Presence of elements of discretization
The equation-based model is formulated with differential equations which are continuous both in population and in time. The time discretization is the result of the different integration steps which in turn are only due to our need to calculate and simulate. On the opposite, the agent-based model is intrinsically discrete both in population and in time. The minimum components of the system are the agents which are discrete by definition. Also, the time steps are finite and discrete.

8. Exploiting the educational potential of equation-based and agent-based simulations in the light of the OECD framework

As we anticipated in the introduction, we discuss the results of the epistemological analysis of equation- and agent-based models and simulations in light of the OECD Learning Compass 2030. In particular, the analysis is discussed in terms of its contribution to the characterization of the Anticipation-Action-Reflection (AAR) cycle and the transformative competencies reported in the OECD Learning Compass 2030 framework [18]. Recalling the description provided in section 2.4, now we can go through the three categories of comparison between equation- and agent-based approaches and discuss how they can be related to the OECD components of the AAR cycle and to the transformative competencies.
The first criterion of comparison, highlighted by Lens 1 (Relationship between system's levels) can be interpreted within the Action and Reflection components of the AAR cycle, and the transformative competency of reconciling tensions and dilemmas. We recall from our analysis that this category refers to the distinction between the direction in which knowledge on the system is provided. For this distinction, an outstanding concept is that of emergent property: a pattern or behaviour which is typical of the global level of the system and depends non-linearly from the local interactions among its components. In this perspective, action becomes an important concept. Indeed, as clarified in the previous paragraph about the continuous vs discrete category, an action is always initiated by individual agents. In particular, actions are usually inter-actions among at least a couple of agents in the systems. However, actions and interactions produce not only local effects (for example in the couple of two acting individuals) but also global ones. Instead of being produced by top-down indications, complex behaviour eventually emerges from the collection of actions and interactions of the individuals in a bottom-up way. Acting in such a complex system as society is a delicate matter which requires Reflection. Indeed, the local level of individual actions and the global level of societal behaviour feedback on each other, making the recognition of a linear cause-effect chain problematic. This needs planning, but in a perspective that contemplates the role of

uncertainty and unpredictability, without neglecting them. In this process of planning and reflection, the role of transformative competencies can be exploited. In particular, it is important to recognize the tensions between the local level of individual interests and values, and the global level of societal needs. Responsible agents are able to problematize this tension and act in a way to reconcile it.

Lens 2 (Probabilistic nature) regards a criterion that can be read in the light of Anticipation, Reflection and to the transformative competency of creating new value. The link with Anticipation lies in the fact that the introduction of probability within the description of a system makes impossible to predict its evolution with arbitrary accuracy. Probability indeed leads not to a univocal, a priori determined future, but to a plurality of possible scenarios. This is displayed also by the SIR model: while the equation-based models and simulations are deterministic and produce the same results every time they are run, the agent-based models embed probability in such a profound way that different results are obtained every time. The probabilistic nature of agent-based models also creates rooms for uncertainty, which is neglectable in the deterministic equation-based models. This connects the determinism vs probability category with Reflection of the AAR cycle too. Indeed, the recognition of the different levels of uncertainties in the issue at stake leads to evidence-based reasonings and reflections. Uncertainty has not to be considered only as something that hinders planning and acting but its productive role should also be acknowledged. In the multiplicity of possible scenarios, the creativity of the individuals becomes very important. Far from remaining attached to an already explored world, individuals can create new value for themselves and for society with their own actions, engaging in a process of transformation conceptualized within the OECD transformative competencies.

Finally, Lens 3 (Presence of elements of discretization) can be used to shed light on Action of the AAR cycle and with the transformative competency of taking responsibility. The conceptual and epistemological analysis of the SIR model has shown a radical difference in conceiving the population, according to the equation- and agent-based approaches. In the former the population is an undifferentiated whole, while in the latter it consists of individuals, named agents. Thinking a population not as an abstract continuous entity that changes in size over time but as a set of individuals puts the very same idea of action in a different perspective. Actions are performed by single persons, and one cannot expect that “the society”, “the population”, “the citizenship” - according to the equation-based meaning - act. Each citizen, as member of society, has his/her role and, as a consequence, his/her actions matter. Reading all this in the light of the transformative competencies, this is strictly connected with the competency of taking responsibility: recognizing themselves as agents, they become responsible for their actions and omissions.

9. Exploiting the educational potential of equation-based and agent-based simulations to develop future-scaffolding skills

The nexus between complexity and agency across the three categories can also be read in the light of future-scaffolding skills (Levrini et al., 2019; Levrini et al., 2021), summarized in Table 5. They have been defined as “skills to structure ways of thinking about the present, the futures and their back-and-forth relations” (Levrini et al., 2021). We recall that two types of future-scaffolding skills have been recognized: structural (St) and dynamical (Dyn). The former refers to the abilities to construct a rational scaffolding and systemic views of the present and the futures, recognizing temporal, logical and causal relationships. The latter relates to the abilities to navigate across the scaffolding, connecting local details to global views, past to present and future, and individual to collective actions. Future-scaffolding skills have been argued to play an important role in science education, as mediators between the disciplinary knowledge, represented by the so-called future-oriented scientific issue (FoSI) at stake, and the development of student agency, as interpreted by OECD. In the followings, we go through the conceptual and epistemological analysis of the SIR model to show how it is a disciplinary resource to develop future-scaffolding skills.

The conceptual analysis of the SIR model and simulations mainly contributes to the development of structural skills. Students are guided to distinguish between disciplinary details of the model and the comprehensive picture of the problem addressed (St1), to unpack the model in its parts (mathematical model, computational model, simulation) (St2), to recognize causal relationships embedded in the model (St3) and other aspects related to its formulation, like the relationship between assumptions and reality (St4).

Coming to the comparison of equation- and agent-based models and simulations, the focus moves from the construction of a rational scaffolding (structural skills) to the development of skills to navigate back and forth this scaffolding (dynamical skills). In particular, three dynamical skills are the objective of the epistemological comparative analysis: move from thinking locally to thinking globally and vice versa (Dyn1), move from thinking at the present to thinking at the future and vice versa (Dyn2), move from thinking at the individual to thinking at the societal community and vice versa (Dyn3). Even if these three skills are strictly connected, a one-to-one correspondence can be established with the three categories of comparison.

Reflecting, through Lens 2, on the probabilistic nature of the models mainly impacts the perception of the future (Dyn2) that, from being a priori determined and computable (as the equation-based models suggest), becomes subject to probability (as shown by the agent-based models). In this way, moving from the present to the future is not a deterministic univocal procedure, but requires a vigilant attitude to consider the known data and conditions to think at the possible evolutions of the system.

Lens 3, with its focus on the presence of elements of discretization, paves the way for the development of the skill to move across thinking at individuals and thinking at society (Dyn3). Indeed, thinking at individuals refers to a discrete, agent-based perspective where the actions, values and needs of the different agents are considered. Thinking at society relates instead to a continuous, equation-based perspective where there are values and goals that characterize not a single person or a small group but the community as a whole. Being able to consider the importance of these two perspectives touches the earth of this dynamical skill.

Strictly related to the Lens 3, Lens 1 with the reflection on the relationships between the levels of a system, is mainly connected to the skill of thinking locally and globally (Dyn1). In a bottom-up, agent-based perspective, the starting point is the local level of agents, while in a top-down, equation-based perspective, the primary focus is the global level of population. However, to gain a rich understanding of the complex issue at stake, the two perspectives are far from being autonomous or detached. The local focus of the agent-based approach is only the starting point of the analysis: then, measures on the system are performed to observe global behaviour that do not lie in the individual components. Conversely, the focus on the aggregate level of the equation-based approach is followed by the analysis of what happens at a more local level.

10.Conclusions

The SIR model has been chosen as a research topic by the authors for very contingent reasons. In the first quarter of 2020, the COVID-19 pandemic was ravaging, and the SIR model became of worldwide interest. Newspaper articles, blog posts and Instagram stories cited this model to inform their audience and support them to make sense of the on-going emergency. Also, according to Google Trends, queries for terms like “SIR model” or “SIR model differential equations” recorded huge hikes from the end of February to mid-May, 2020, firstly in China and then in other countries, following dramatically the discovery of COVID-19 cases all over the world. In this context, at the beginning of March, we started the present work with the goal of clarifying the disciplinary contents of such a trending topic and design a lecture targeted to university Physics and Mathematics students enrolled in a course of Physics Education.

While the study and the lockdown were going on, we realized that beyond the strictly technical and conceptual aspects, the topic of SIR model and simulations raised epistemological issues that touched the heart of the scientific enterprise. In particular, the distinction between equation- and agent-based approaches to modelling and simulating was illuminating, and it was articulated across three categories of comparison: relationship between system’s levels, probabilistic nature, and presence of elements of discretization. These categories are all but new for science. They embody important debates that had a big role in the history of science and, even nowadays, they are far from being solved. For example: what is the role of mathematical modelling to understand the world? In this way, writing the chapter has been the opportunity to explore the SIR model not *per se*, as a technical exercise, but as a case study that shows the role of models and simulations to reflect on the paradigm change of contemporary science that has determinism vs probability, continuous vs discrete and top-down vs bottom-up as focal debates.

Finally, when the first hard lockdown in our country had ended, we looked at the conceptual and epistemological analysis as researchers in science education and we asked ourselves: how our work should matter to students and citizens not only in the contingency of a lockdown to make-sense of what is happening, but also hopefully beyond an emergency situation? Indeed, we strongly believe that education should not only provide answers to urgent specific issues but to develop ways of looking at the problems from a wider perspective, within which also the specific issues can find their answers. To do that, the discussion exploited the nexus between complexity, embedded in the three categories of comparison, and agency, at the basis of the OECD framework. It allowed to connect two apparently distant worlds. One has its core in the scientific discipline (with elements from mathematics, physics and computer science) and is represented by the conceptual and epistemological analysis performed on a very specialistic topic such as the SIR model and simulation. The other is the world of educational recommendations, represented in this case by the OECD

Learning Compass. Both have their own languages and look at education from their perspective. However, they are not separated since, we argue, they need one each other to be authentic and relevant. How could science education be relevant to tackle with the complexity of the present if the perspective of agency, transformation and engagement were not considered? And, conversely, how could science education be authentic if the disciplines were not addressed in depth in their conceptual, epistemological and methodological aspects?
In this light, we have discussed the role of future-scaffolding skills as mediators between complexity and agency. The structural skills are needed to construct a systemic understanding of the issue at stake (in our case, the spread of an infectious disease), while the dynamical ones are needed to navigate this complexity, paving the way to students' agency in a complex system.
Further work on this topic has already started. Within the Erasmus+ Project "IDENTITIES" (www.identitiesproject.eu), the interdisciplinarity of the models and simulations will be explored and the conceptual, epistemological, and educational dimensions will be addressed with prospective teachers during innovative activities (Barelli et al., submitted).

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Remarks from Part 2

In the second part of the dissertation, we have reported two analyses conducted during the second and third year of the Ph.D. program that together constitute the conceptual and epistemological core of the thesis. Examining the case studies of the artificial neural networks and the SIR epidemiological model and its simulations, we tried to guide the reader in recognizing how machine learning and computational simulations are two fields that relate, in different ways, to the cultural, epistemological, and societal revolution brought by the science of complexity. The work and the goals of this part were two-pronged. On one side, we wanted to investigate the epistemological revolution of complexity through machine learning and computational simulations. On the other, we realized that the epistemological categories of complexity that we were highlighting had become for us the way to recognize in artificial neural networks and in the SIR model two complex models that reflect in a computational artifact the cultural revolution brought by the complexity science. In this sense, at the end of this part, we notice a circularity – to go on with the vocabulary of complexity – between the specific case studies and the broad epistemological level: the perspective of complexity was the lens through which analyzing the neural networks and the SIR simulations but, conversely, the disciplinary and technical analyses of these objects made our lens sharper and enriched of substantial details our view of the revolution brought by the science of complex systems. However, our analyses were not limited at the conceptual and epistemological level, since the focus was always on the educational dimension as, for example, the focus on the OECD framework and future-scaffolding skills of Chapter 5 has shown. In the light of the fundamental principles of Duit's model, we consider this Part 2 as the part of educational reconstruction, or *pars construens*, of the dissertation. Indeed, it sets the basis, on a multiplicity of levels, for the design and implementation of the teaching proposals that will be presented in the third part.

For the story told in this dissertation, the two studies of Part 2 constituted the epistemological heart of the thesis since allowed us to:

- obtain an educational reconstruction of neural networks and computational simulations from the perspective of complexity;
- identify in the comparison between different approaches a way to illuminate the features of the cultural revolution of complexity;
- develop a prototype of analysis of computational simulations for educational purposes;
- recognize the interdisciplinarity embedded in computational simulations;
- point out the potential of agent-based simulations to trigger agency and future-scaffolding skills;
- understand that the perspective of complexity applied to simulations can become an epistemological lens to imagine the future.

Part 3

In Part 3, we present two educational proposals targeted to university Physics and Mathematics students and to secondary school students on the topic of simulations of complex systems. Their design and implementation phases took place during the third and fourth year of the Ph.D. program. In both chapters, the data analyses are conducted to exploit the role of simulations as the scientific basis for the development of decision-making and future-scaffolding skills. Extended sections are dedicated to the description of the teaching-learning modules, grounded on the empirical results of the studies of Part 1 and the educational reconstruction of the contents presented in Part 2.

Chapter 6 - Computational simulations to support decision-making processes[15]

1. Introduction

In the first part of this thesis, we have seen that it can be very difficult for novices to recognize in computational simulations of complex societal systems authentic forms of scientific knowledge. Indeed, simulations are often perceived as kinds of games that refer to a fictional world and, because of that, cannot suggest concrete actions or support relatable decision-making processes.

For the study we present in this chapter, we decided to address with university Physics and Mathematics students a particular agent-based simulation that was developed by physicist within a Horizon2020 project to o support policymakers in decision-making on a complex problem: the formation of terrorist groups. We found this problem particularly well-positioned to respond to the criticisms raised by the previous studies because it was an intrinsically complex problem that could inspire an authentic decision-making process. Indeed, as we will extensively show in this chapter, the formation of terrorist networks can be modelled on the basis of local mechanisms of interaction inspired to the theory of opinion dynamics: the mechanistic local description of how people exchange their opinions through one-to-one interaction eventually leads to global phenomena of polarization. Guiding the students to explain these non-trivial local-global relationships within a concrete societal problem allowed the students to touch the very heart of complexity science. Moreover, the use of a complex simulation – much more articulated than those usually used to teach complexity science – made us reflect on the different kinds of scientific information that a simulation and the related model vehicle. This un-packing of the knowledge elements behind a simulation led to the design of a role-play activity proposed to university Physics and Mathematics students on the issue of terrorist groups' formation.

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[15] The contents of this chapter have been presented in the invited oral presentations at the SIF 2020 Congress (Barelli, 2020) and in the extended abstract selected for a round-table presentation at the AERA 2021 Annual Meeting (Barelli & Levrini, 2021). The analysis has been discussed within the ESERA 2020 Virtual Doctoral Network.

2. The need of decision-making skills to deal with complex societal challenges

If the computational simulations have become the third pillar of scientific research (Parisi, 2001; Hey, Hansle & Tolle, 2007), their use nowadays is not restricted to the fields of the so-called "hard sciences" because they have become a prominent tool also for the "social sciences". An example of this transition can be found in the model (and simulations) of the biological contagion, analyzed in Chapter 5 with the SIR model. Indeed, as Vespignani recalls: "The "biological contact theory" is a valid conceptual frame for a wide panorama of phenomena of diffusion and contamination that have nothing to do with the biological world. The diffusion of ideas, new knowledge, political choices, fashion, are all contagion phenomena in which some individuals "infect" other individuals through interactions that day by day define our social network" (Vespignani, 2019, p. 204). The agent-based approach to modelling and the network theories are what have made possible the transfer and sharing of tools between domains that were originally perceived as very distant.

Being a crucial tool of the passage from hard to social sciences, computational simulations have become of outstanding importance in modelling, describing, explaining, visualizing, and making decisions about societally relevant topics. We can think for example at climate change and, even more recently, at the COVID-19 pandemic. In these cases, the idea of "science for specialists" have been challenged, with non-expert policymakers that have been calling to decide which political actions and to structure their policy programs also on the basis of models and simulations and of the results they provide. Conversely, the process of decision-making does not regard only few actors but is extended up to a variety of stakeholders (from councilors with different expertise to lobbyists) and, in the end, to citizens as members of democratic societies (del Río, Navarro & Font, 2016). Moreover, the on-going crises require all these actors to make decisions on many topics in a relatively short period of time, as the pandemic emergency has shown, also revealing the major inadequacy of most decision-makers to make efficient and consistent decisions. The issue of decision-making during a crisis is intrinsically complex since in times of crisis, the uncertainty, complications, ambiguity, lack of insight increase, and the ability to make wise decisions decreases (James & Wooten, 2005). In a context in which knowledge is unavoidably fragmented, decision-making is an art of compromise, where an option or an intervention has to be chosen of a set of specific alternatives (Al-Dabbagh, 2020).

To move across the complexity of the issues addressed and to articulate a reliable decision-making process, many authors have advocated for the necessity to equip the decision-makers at any level – from the democratic base of citizenry to the most influential leaders and spokespersons – with decision-making skills (e.g. Bingle & Gaskell, 1994; Al-Dabbagh, 2020; Lee, 2007; Mettas, 2011). Despite these claims, only few authors explicitly name, characterize, and operationalize these skills. For example, Al-Dabbagh (2020) identifies, through interviews with policy makers, the following set of skills that are particularly important to respond to an on-going crisis but that we can generalize for any societally relevant decision-making process: 1) Collecting information about the issue under study; 2) Developing alternatives and possible solutions; 3) Comparing and choosing among the available alternatives to face the issue; 4) Predicting the consequences of possible solutions and alternatives; 5) Analysis, correlation, and conclusion; 6) Evaluating the results of solutions taken to

face the issue; 7) Diagnosing the current situation; 8) Communicating with the parties; 9) Solving problems using traditional and creative methods; 10) Critical thinking.
If most of us can certainly acknowledge the importance of each of the mentioned skills, defining them in a way that is rigorous enough to be "operational" and, hence, can suggest ways to recognize them in decision-making contexts is a problem that nowadays remains open. In the study we present, we want to go beyond the appearance of "common sense" skills that such a list can suggest. On one side, we illustrate the design principles of a role-play activity involving a decision-making process, guided by the goal of triggering specific skills. On the other, we monitor through the data analysis which skills did the activity foster and which remained inactivated even if were *a priori* expected. In particular, we argue how computational simulations play a role in the development of these competencies. The novelty of this approach is that the same simulation is both the object on which the decision-making has to rely and the tool to develop such skills.

3. Conceptual analysis of two agent-based simulations

Within the wide set of simulation tools, two main categories can be distinguished (Grüne-Yanoff & Weirich, 2010): the equation-based and agent-based ones. In the former case, the evolution of a target system is described by differential equations; once they are numerically solved, they allow to determine the future state of the system starting from the present state. On the opposite, in agent-based simulations, the dynamics of the target system is generated making the individual agents evolve according to behavioral rules. More on this crucial distinction and the role that it has within the educational community can be read in Chapter 5 (Section 2.4).
In this section we will present the conceptual analysis of two agent-based simulations and the respective models that are at their basis. Indeed, the Axelrod simulation on the dissemination of culture and the PROTON simulations on the formation of terrorist networks are the main conceptual tools on which the module for university students has been designed.

3.1. The Axelrod's model and simulation

The Axelrod's model is an agent-based model of culture dissemination (Axelrod, 1997). It describes how the cultures of individuals (their opinions on certain topics) interact by producing the cultures of the population. In the model, even if the local interactions among agents increase their similarity, a global phenomenon can be observed with the simulation: the emergence of patterns of polarization, i.e. zones with potentially completely different cultures.

3.1.1. The model

Before focusing on its implementation in a computational simulation, we analyze the core aspects of the model. In presenting them, we will make extensive use of excerpts of the article, but a comment and discussion will always be provided to frame the quotations within the argumentation we want to develop.

The definition of culture

From the title itself of the paper "The dissemination of culture: a model with local convergence and global polarization" emerges that conceptualizing what is "culture" is of crucial important for the author. In front of the wide literature and the variety of ways to define culture (Kroeber & Kluckhorn, 1952; Birukou, Blanzieri, Giorgini & Giunchiglia, 2013), Axelrod does not want to provide his own theorization. Within its model, he considers culture as what can be subject to social influence. Using the author's words:

> *"Unfortunately, no good term describes the range of things about which people can influence each other. […] The most generic term for the things over which people influence each other is culture. Therefore, the term culture will be used to indicate the set of individual attributes that are subject to social influence"* (Axelrod, 1997, p. 203-204)

Or, later:

> *"Culture in something people learn from each other"* (Axelrod, 1997, p. 206)
> *"Culture is taken to be what social influence influences"* (Axelrod, 1997, p. 207)

This way of thinking at the idea of culture is fundamental for the development of the model itself. Indeed, in the definition that the author considers there is already the seed for asking "how does culture change". We will see in the followings how the paper tries to provide an agent-based mechanism to answer this question.

Moreover, the author does not conceive culture as a unique "thing" which can change as a whole, but imagines it as a "set of individual attributes" that describe different cultural aspects:

> *"The model assumes that an individual's culture can be described in terms of his or her attributes, such as language, religion, technology, style of dress, and so forth"* (Axelrod, 1997, p. 208)

Someone would argue that this way of unpacking something as broad as a culture in a list of attributes recalls a reductionist perspective that could seem to go against the basics of social sciences. However, we argue that this choice of the features to consider is embedded in all modelling acts and, in particular, agent-based models are explicitly non reductionist since they make emergent properties visible (Jackson, Rand, Lewis, Norton & Gray, 2017).

The goal of the model

With the given conceptualization of culture, the author points out the ways in which the social influence acts on individuals' cultures:

> *"People are more likely to interact with others who share many of their cultural attributes, and interactions between two people tend to increase the number of attributes they share"* (Axelrod, 1997, p. 206)

However, if this can be thought as a common-sense norm, it is also evident that our society is not totally homogeneous but different cultures exist. The question to be addressed is then to explain how and why this happens. Reading Axelrod's words:

> *"The question being investigated is how people influence each other on a given set of features and why this influence does not lead to homogeneity"* (Axelrod, 1997, p. 204)

The question is two-pronged. On one side there is the *how* question that suggests the search for a mechanism to account for social influence; on the other we have a *why* question that requires an explanation for an emergent phenomenon (the not-homogeneity of the system) based on a local behavior (the cultural influence between people).
Coherently with his question, the author clarifies since the beginning that the aim of the model is not the prediction of facts but consists rather in showing what some behavioral rules can lead:

> *"The model is not intended to predict any particular historical events. Instead, it is meant to show the consequences of a few simple assumptions about how people (or groups) are influenced by those around them"* (Axelrod, 1997, p. 206)

<u>The basics of the model</u>
We have already commented that, for the author, the culture of an individual can be described as a set of cultural attributes. Passing from the model's assumptions to the modelling language, the author associate to each agent a culture that is described as a list of *features*, where each of these features can have a certain number of alternative values, named the *traits*:

> *"Because the model can be abstract about the specific content of an individual's culture, it describes a culture as a list of features or dimensions of culture. For each feature there is a set of traits, which are the alternative values the feature may have"* (Axelrod, 1997, p. 208)

The agents with their own cultures are organized in a grid that provides the geography of the model and the topological measures of proximity that determine the range of interaction among site of the grid and, hence, among agents:

> *"The model includes a geographic distribution of individual agents. […] The sites are the basic actors of the model. Each site can interact only with its immediate neighbors."* (Axelrod, 1997, p. 208)

Once the author has defined the agents and their geographical arrangement, he is ready to give the formal statement of the dynamic of the model.

> *"The process of social influence in the model can be described as a series of events. […] Repeat the following steps for as many events as desired.*
> *Step 1) At random, pick a site to be active, and pick one of its neighbors.*
> *Step 2) With probability equal to their cultural similarity (percentage of their features that have identical traits), these two sites interact. An interaction consists of selecting at random a feature on which the active site and its*

neighbor differ (if there is one) and changing the active site's trait on this feature to the neighbor's trait on this feature." (Axelrod, 1997, p. 208)

To clarify this with an example, let's assume that a culture is described by 5 cultural features, each of them can have 10 values (from 0 to 10). Possible agents would be represented as: (1, 8, 8, 2, 3), (1, 9, 0, 9, 2), (3, 4, 8, 5, 0), and so on. Now, we imagine that on step 1 we select an agent with (8, 2, 3, 3, 0) as the active agent and (6, 7, 7, 3, 0) as its neighbor.
In step 2 we have to calculate the probability of interaction as the percentage of features that have identical traits. In this case they interact with 40% probability, since 2 features out of 5 have identical traits.

Active (8, 2, 3, 3, 0)
↕↕
Neighbor (6, 7, 7, 3, 0)

To complete step 2, if they happen to interact, the active agent gets the trait of the neighbor on a random feature that they do not share. In this case, assuming that the two agents interact, we could select the first feature and the active agent would get 6 instead of the former 8.

Active (6, 2, 3, 3, 0)
↑
Neighbor (6, 7, 7, 3, 0)

We notice that the direction of influence goes, for each couple of agents, only from the neighbor to the active, being the other direction impossible for the rules of the model.

The emergent phenomena

On the basis of the microscopic rules specified by the dynamics of the model, different phenomena are observed on the macroscopic scale of the system. Before commenting the collective behaviors, we discuss briefly how the author moves from the microscopic to the macroscopic level.
In this excerpt, for example, we read:

"To make the development of cultural regions more apparent, we can shift our attention from the details of the culture at each site to the cultural similarities between adjacent sites" (Axelrod, 1997, p. 209-210)

To develop his argumentation, the author guides the reader to point the attention rather than on the individual agent to the couple of adjacent sites. Focusing on adjacent sites, the author can now define the cultural region which can be interpreted as the mid-level (Levy & Wilensky, 2008) of the system:

"A cultural region can be defined as a set of contiguous sites with an identical culture." (Axelrod, 1997, p. 211)

With these definitions, the author can proceed explaining the first emergent phenomenon that is the development of different cultural regions:

> *"Initially, most neighboring sites have little in common with each other and hence are unlikely to interact. However, when two sites do interact, they become more similar and hence are more likely to interact in the future. […] Over time, specific cultural features tend to be shared over a larger and larger area. Indeed, regions start to form in which all the features are exactly the same."* (Axelrod, 1997, p. 211)

The author's explanation starts from the microscopic level of the individual agents (the "neighboring sites") and of their one-to-one interaction ("when two sites do interact"), passes through a mid-level made of areas in which the cultural features spread ("cultural features tend to be shared over a larger and larger area"), and arrives to the macroscopic level in which stable cultural regions are formed ("regions start to form in which all the features are exactly the same").
We notice that this is a typical expert explanation that can be formulated to account for an emergent phenomenon. Moreover, in this explanation is underlined a feedback effect that can be observed as a consequence of the recurrent implementation of the model's rules. Indeed, saying that "when two sites do interact, they become more similar and hence are more likely to interact in the future", we are making explicit the presence of a positive feedback effect that reinforces the similarity between already partially similar agents.

The second emergent phenomenon that can be observed is the so called "majority wins" phenomenon. It is observed when in the system are formed two cultural regions differing in a single feature. The author uses the term "dialects" to describe these cultures since they are very similar except that for one feature. In this case we observe that the largest region tends to "eat" the smallest one, with the largest dialect that has more probability to include the less common one than the other way around. Axelrod explains this emergent behavior, that is not in any case codified within the rules of the model, saying that in a situation in which there are only two similar cultural regions:

> *"[…] the only possibility for change would be if the active site were in one region and its selected neighbor in the other. The consequence would be that the boundary between the two regions would move by one site, either to the east or west. Moreover, these two possibilities are equally likely. […] The movement of the regional boundary follows a process known as a random walk with absorbing barriers. […] stability will be reached when the boundary between the regions moves all the way to east or the west – that is, when one dialect has completely "eaten" the other dialect. An interesting thing about this illustration is that the larger region is more likely to "eat" the smaller region than the other way around because the random walk of the boundary is more likely to reach the nearer edge of the map before it reaches the further edge. Thus the majority culture is more likely to survive than the minority culture, even though there is absolutely no bias in the process of social influence."* (Axelrod, 1997, p. 216)

The author's explanation is particularly interesting because interprets the rules of the model in this specific case as a type of random walk in which what "walks" is not an agent, nor a culture but the *boundary* between the cultural regions.

Even if, given the values of parameters and the initial configuration of the system, is not possible to predict the final configuration of the system, the probability of observing global phenomena of convergence or divergence (polarization) changes depending on the number of features considered, on the number of traits that each feature can have, on the radius of interaction and on the same number of agents. Let's examine each of them presenting the author's explanation.
When the number of features grows there is more likelihood to reach a global cultural convergence, meaning that the agents reach the same culture. This is a counterintuitive behavior since we would believe that adding more attributes to describe a culture would increase the variability of the agents and, consequently, hinder convergence. However, it is observed the opposite:

> *"because with more features there is a greater chance that two sites will have the same trait on at least one feature and therefore will be able to interact. With interaction comes the sharing of the trait on an additional cultural feature. So with more features in the culture there is a greater chance neighbors will have something in common, and thus they will have a greater chance to attain complete cultural convergence with each other."* (Axelrod, 1997, p. 212)

The opposite happens when grows the number of cultural traits that leads to a higher probability of polarization:

> *"When there are few features and many traits, there is a good chance that two neighbors will share no features and thus be unable to interact. This, in turn, makes it easier for many distinct regions to form, each of which has no features in common with any adjacent region."* (Axelrod, 1997, p. 212-213)

Another thing that can be changed is the radius of interaction, namely the number of neighbors that can share their culture with a given agent. In this case, increasing the radius makes convergence easier.
The last, and more refined phenomena to explain is the dependence of the chance to observe convergence or polarization on the number of agents in the system. If, applying a classical, linear and proportional reasoning, we could expect to the more agents correspond more cultural regions, what is observed is that small and large territories have few stable cultural regions while moderate-sized territories have the largest number of stable territories. The author explains it in the following way:

> *"Why do moderate-sized territories have the largest number of stable territories? It is no surprise that smallest territories have the fewest stable regions. After all, small territories simply do not have enough sites to contain many different cultures. So it is not surprising that as the size of the territory increases from, say, 2x2 sites to 12x12 sites, the number of stable regions increases. What is really surprising is that as the size of the territory increases further, the number of stable regions actually decreases. So why do large territories have fewer stable regions that moderate-sized territories? […] One might also wonder whether the phenomenon of large territories having fewer stable regions has something to do with the existence of boundaries on the territories. Boundaries can be eliminated by wrapping around the northern and southern edges and the eastern and western edges. Simulations with this neighborhood topology show the same pattern as before. So the existence of territorial boundaries is not the cause of large territories having fewer stable regions than moderate-sized territories."* (Axelrod, 1997, p. 215)

"Recall that a cultural region is a set of contiguous sites with identical cultures. A related idea is a cultural zone: a set of contiguous sites, each of which has a neighbor with a "compatible" culture. Cultures are compatible if they have at least one feature in common." (Axelrod, 1997, p. 217)
"Over time, boundaries between regions in the same cultural zone tend to dissolve. […] On the other hand, adjacent sites in different cultural zones cannot interact because they have no cultural features in common. This is why boundaries within cultural zones tend to dissolve, but boundaries between cultural zones tend to be stable. Nevertheless, even boundaries between cultural zones can dissolve." (Axlerod, 1997, p. 218)
"Another way of looking at the dynamic process is to consider how alternative traits for a cultural feature move around in a zone as neighboring sites interact. As long as there are many regions within each zone, there are different cultural traits for at least some of the features in the zone. As these traits move around in the zone through interactions, they have a chance of dissolving boundaries, both regional and zonal. The net effect is that the more time it takes for a territory to settle down, the more chance there is that zonal and regional boundaries will be dissolved. Large territories take much longer to reach stability than smaller territories, and this gives the regional and even zonal boundaries in large territories more opportunities to dissolve." (Axlerod, 1997, p. 218-219)

We emphasize how the author in his explanations never uses a vocabulary of necessity but rather a language of probability.

<u>The characterization of the model as an agent-based model</u>
The author explicates the features of his model that make it belong to the wider category of agent-base models. They are:
- The bottom-up character
- The lack of central authority
- The presence of adaptive agents

The first feature is the bottom-up character of the model. Indeed, it sets local rules for the agents and from these mechanisms and from the combined interaction of many agents the emergent properties of the system arise:

"Mechanisms of change are specified for local actors, and then the consequences of these mechanisms are examined to discover the emergent properties of the system when many actors interact." (Axelrod, 1997, p. 207)

The main systemic phenomenon displayed in the model is the global divergence of cultures. Since it is a result of local rules of convergence, which are the only rules explicitly coded, we can say that the separation of cultures (also called polarization) is the main emergent property of this model:

"Polarization occurs in the model, even though the only mechanism for change is one of convergence toward a neighbor. Thus, when polarization is seen, it need not be due to any divergent process. Likewise, when cultural traits are highly correlated in geographic regions, one should not assume that there is some natural way in which those particular traits go together. The social influence model shows how homogeneous cultural regions can arise without any intrinsic relationship between the separate dimensions that become correlated." (Axelrod, 1997, p. 220)

The second feature that makes the Axelrod's model an agent-based one is the lack of central authority. The collective behavior of the system is not determined by a controller, a designer, a chief or a leader, but are produced by the adaptive behavior of the single individuals:

> *"Consistent with the agent-based approach is the lack of any central coordinating agent in the model. It is certainly true that important aspects of cultures sometimes come to be standardized, canonized, and disseminate by powerful authorities such as church fathers, Webster, and Napoleon. The present model deals with the process of social influence before (or alongside of) the actions of such authorities. It seeks to understand just how much of cultural emergence and stability can be explained without resorting to the coordinating influence of centralized authority."* (Axelrod, 1997, p. 207)

The third feature is specifically related to the characteristics of the agents of the model. They are not rational agents able to decide how to behave depending on cost-benefit analyses. On the opposite, their behavior is coded once for all by the modeler and the agents can only follow these rules:

> *"The individuals are assumed to follow simple rules about giving and receiving influence. […] The agents simply adapt to their environment."* (Axelrod, 1997, p. 207)

3.1.2. The simulation

Starting from the implementation by Rodríguez (2013), we have developed a NetLogo simulation of the Axelrod's model (Barelli, 2021). In this section we describe the interface of the simulation, provide some hints on the use of the model for unfamiliar users and analyze in detail the code behind it.

<u>The interface</u>

Beside the typical functions of the NetLogo simulations (like the Setup, Go Forever and Go Once buttons), the interface of the simulation, reported in Figure 1, is structured horizontally in three parts:

- on the left: the things that the user can modify;
- in the middle; the grid with the agents;
- on the right: the global measures that can be performed on the configuration of the system at each time.

We comment each of these parts in detail.

In the section dedicated to the parameters there are four of them:

- world-size: determines the number of agents and the dimension of the grid. The number of agents is the square of the number indicated by the world-size slider;
- F: the number of cultural features considered;
- q: the number of traits that each cultural feature can have;
- radius: the range of interaction, hence the number of nearest neighbor with which each agent can interact at each simulation's step.

The grid reports human-shaped agents that differ for color which indicates their own culture.

In the right we have on the top part a graph that indicates, over time, the number of cultures in the system. Bottom right there is the “Report Networks” button that can be pressed to obtain measures on the number and dimension of the cultural regions present in the system at a given time.

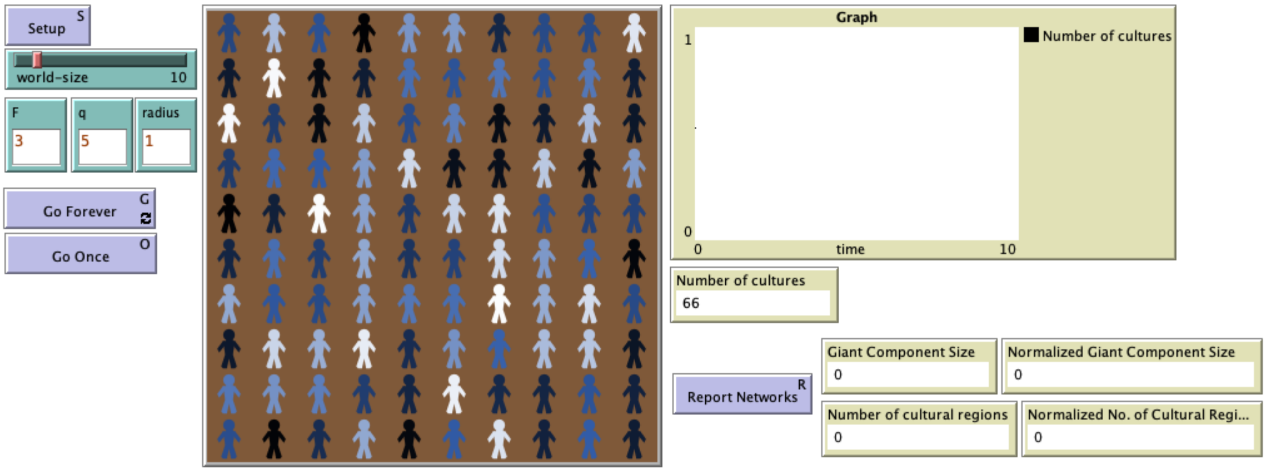


Figure 1. Interface of the Axelrod’s simulation (Barelli, 2021).

<u>Use of the model</u>

For those who are not familiar with the NetLogo language and simulations, after having presented the structure of the interface, we provide some hints of how the simulation can be used.

The user can choose the size of the population (via "world-size"), the number of cultural characteristics considered (F), the number of cultural traits (q) and the range of interaction (radius). When the radius is equal to 1, the neighborhood of each agent consists of the 4 agents immediately above, below, right and left (following the Von Neumann topology). Pressing 'Setup' the user initializes the system with the selected parameters. “Go Once” or “Go Forever” make the simulation start. The simulation allows the user to follow the changes in the culture of the agents based on the color they take on. In addition, a graph reports the number of different cultures at each tick of the simulation. At the end of the simulation, through “Report Networks” it is possible to obtain the number of cultural regions in the population (regions with adjacent agents of the same culture) and the number of agents in the largest region.

As many NetLogo simulation, the one we have designed contains also an information sheet articulated in different sections: a general introduction to the Axelrod’s model, the rules at the basis of the simulation, some indications to use the simulation, some questions to explore some simulated phenomena, the take-home message of the model, and the references.

<u>The code</u>

As all NetLogo simulations, the code structure is strictly dependent on the functioning of NetLogo programming language. NetLogo codes consist of variables and procedures.

The variables can be global, accessible by all agents and that can be used anywhere in the model, or specific for the agents.

The global variables are showed in Table 1 while the agents-specific ones are reported in Table 2.

Table 1. "Globals" variables of the Axelrod's simulation (Barelli, 2021).

Type of the variable	Name of the variable	Meaning of the variable
Variable that increases with the ticks each time the procedure go is executed	time	Time
Variable setup by the user through the world-size slider	number_of_agents	Number of all agents in the society
Variable with fixed value, depending only by the values of F and q set by the user ($q^F - 1$)	cult_max	Number associated to the culture with maximum traits for each feature [q-1, q-1, q-1, …, q-1]
Global variable updated at each tick of the model, based on the count of the essential features of the agents	number_of_cultures	Number of cultures in the society at a certain time
Global variable updated at each tick of the model, based on local properties of overlap between agents	number_of_active_agents	Number of agents which have at least one neighbor with overlap in]0,F[
Mid-level variable calculated with a recursive procedure starting with an agent and connecting all the neighbors with the same cultural features	component_size	Number of agents explored so far in the current component
Global variable that measures the number of components in the system	number_of_cultural_regions	Number of cultural regions simply connected
Global variable	giant_component_size	Number of agents in the giant component

Table 2. "Turtles-own" variables of the Axelrod's simulation (Barelli, 2021).

Type of the variable	Name of the variable	Meaning of the variable
List for the culture of the agent	culture	Essential attribute of the agent
Boolean variable that indicates if the agent is already explored when determining the number of cultural regions	explored?	Feature concerning the procedure of counting cultural regions

We notice that, coherently with the definition we have provided above, the global variables do not change depending on the specific agent we are looking at. For example, global variables are "time" that represent the clock of the simulation, or the number of agents or the number of cultures that exist in a certain moment. On the opposite, the "turtles-own"[16] variables are specific for the individual agents. "Culture" is the main agent-specific variable and consists in a list of the values that the different cultural features have at a given simulated time; each agent has its own culture that can change as the simulation runs.

Beside variables, in NetLogo codes there are also procedures that defines what actions have to be performed on the agents or on the elements of the simulation. In Table 3 all the procedures of the simulation are reported, articulated in procedures of setup, procedures that implement the rules of

[16] In NetLogo the term "turtle" is used to indicate what we call the agent.

the Axelrod's model and additional procedures that are needed to obtain graphs or collective measures of the state of the system.

Table 3. Procedures of the Axelrod's simulation (Barelli, 2021).

Name of the procedure	Scope of the procedure
Setup procedures	
`setup`	General setup settings: clear plots, create the grid
`setup-turtles`	Agent settings: create agents, position them in the grid
`setup-culture-max`	Assigning a value to the culture with maximum traits values
`setup-agent-culture`	Assigning a random culture to each agent
`setup-agent-culture-color`	Setting the color to the agent according to its culture
Main procedure	
`go`	Execute all the local and graph procedures in their order until there are active agents
Local procedures	
`cultural-interaction`	Agents look for a neighbor to interact with
`overlap_between`	Reporting overlap between two agents (range from 0 to F)
`culturally_interacting [target_turtle neighbor_turtle]`	Interaction between a target agent and its selected neighbor
Component exploration procedures	
`explore`	Find all agents reachable from this node (recursive procedure)
`creates-links-with-same-cultural-neighbors-in-neighborhood-of-radio-radius`	An agent creates a link with all its neighbors with the same culture
Global exploration procedures	
`count-cultures`	Counting the number of different cultures in the system
`count-turtles-on-biggest-region`	Counting the number of agents in the biggest cultural region
`find-all-components`	Finding all the connected components in the network and their sizes
Graphs procedure	
`do-plots`	Making plot of the number of different cultures vs time

Once presented the structure of the code, we now analyze in detail how the Axelrod's model has been implemented in the NetLogo agent-based computational simulation.
To start the simulation, the first action that needs to be done is the initialization of the agents each of them needs to get its own culture assigned. This is realized through the setup-agent-culture procedure as described in Table 4.

Table 4. Code and pseudo-code for the procedure of initialization of agents' cultures (Barelli, 2021).

Code	Pseudo-code

to setup-agent-culture
  ask turtles [
    set culture []
    repeat F [
      set culture lput random q culture
	All agents, in a random order, are asked to
	set their own variable "culture" to an empty list, then,
	F (number of cultural features) times,
	add at the end of the list a random value in [0, q-1].
	Once the list is filled,

] setup-agent-culture-color] end	set a color for the agent according to its culture

Then the specific rules of interaction need to be coded. We recall the Axelrod's formulation

> *"The process of social influence in the model can be described as a series of events. […] Repeat the following steps for as many events as desired.*
> *Step 1) At random, pick a site to be active, and pick one of its neighbors.*
> *Step 2) With probability equal to their cultural similarity (percentage of their features that have identical traits), these two sites interact. An interaction consists of selecting at random a feature on which the active site and its neighbor differ (if there is one) and changing the active site's trait on this feature to the neighbor's trait on this feature."* (Axelrod, 1997, p. 208)

The step 1 of the model is realized through the cultural-interaction procedure that allows to select a neighbor of the active agent to interact with. It is reported in Table 5.

Table 5. Code and pseudo-code for the procedure of selection of a neighbor (Barelli, 2021)

Code	Pseudo-code
to cultural-interaction	
let number_of_possible_neighbors count other turtles in-radius radius with [(0 < overlap_between self myself) and (overlap_between self myself < F)]	count the neighbors within the given radius that have a number of common traits in]0, F[
if number_of_possible_neighbors > 0 [	if there is one or more such neighbors,
set number_of_active_agents number_of_active_agents + 1	increase of 1 the number of active agents and
let neighbor_turtle one-of other turtles in-radius radius	select a neighbor within the radius
let target_turtle self	
culturally_interacting target_turtle neighbor_turtle	and make it interact with the target agent
]	
end	

To implement the step 2 on a computational model, two procedures are needed. One (to-report overlap_between) is needed to calculate the overlap between the agents, so how many features they have in common. It is reported in Table 6. The other (culturally interacting) is to make actually interact the two agents. It is reported in Table 7.

Table 6. Code and pseudo-code for the procedure of cultural similarity calculation (Barelli, 2021).

Code	Pseudo-code
to-report overlap_between [target_turtle neighbor_turtle]	
let suma 0	Initialize to 0 a temporarily variable suma, then
(foreach [culture] of target_turtle [culture] of neighbor_turtle	for each element of the cultures of target and neighbor,

[[a b] -> if a = b [set suma suma + 1]]	compare the traits and, if they are equal, add 1 to suma
)	
report suma	return suma
end	

Table 7. Code and pseudo-code for the procedure of cultural interaction between the agents (Barelli, 2021).

Code	Pseudo-code
to culturally_interacting [target_turtle neighbor_turtle]	
let overlap overlap_between target_turtle neighbor_turtle	Calculate the overlap between target and neighbor.
if (0 < overlap and overlap < F) [	If the overlap is in]0, F[,
let prob_interaction (overlap / F)	call overlap/F the probability of interaction, then,
if random-float 1.0 < prob_interaction [	according to this probability,
let trait random F	select randomly a cultural feature to inspect
let trait_selected? false	
while [not trait_selected?] [	
ifelse (item trait [culture] of target_turtle = item trait [culture] of neighbor_turtle)	if that cultural feature has the same trait for both agents
[	pass to the adjacent cultural feature
set trait ((trait + 1) mod F)	
]	otherwise
[	
set trait_selected? true	
]	
]	save the trait for that cultural feature of the neighbor
let new_cultural_value (item trait [culture] of neighbor_turtle)	and replace the original cultural feature in the target agent with the neighbor's trait
set culture replace-item trait culture new_cultural_value	update the agent color according to the new culture
setup-agent-culture-color	
]	
]	
end	

We can comment that the computational model we formulated to arrive to the computational simulation in equivalent to the model enunciated by Axelrod in the paper. However, they differ in many ways. When we pass from the model to the computational model, we have to specify exactly the operations that need to be done to implement the steps of the model “on paper”. For example, what on paper is summarized as “with probability equal to their cultural similarity, these two sites interact”, the computational model needs to include instructions to: 1) calculate the cultural similarity between two agents, 2) transforming it into a probability of interaction, 3) “throw a dice” to decide if the interaction can happen or not, and 4) start the interaction. The un-packing of steps expressed in a common, even if precise, language in operational steps that can be read from the machine as instructions is a very typical procedure when we have to transform a model “on paper” into the respective, equivalent, computational model.

The Axelrod's model would be completely implemented only using the procedures seen so far, but in the simulation we add two other procedures that measure the number of different cultures in the system, the number of cultural regions and the size of the giant component. The first procedure is called count-cultures and it is concretely used to plot in real-time the number of different cultures. It is shown in Table 8. The other procedure is called find-all-components and is reported in Table 9.

Table 8. Code and pseudo-code for the procedure that counts the number of different cultures in the system (Barelli, 2021).

Code	Pseudo-code
to count-cultures	
let list_of_cultures []	Initialize an empty list to contain the different cultures.
ask turtles [	All agents, in random order, are asked to
set list_of_cultures lput culture list_of_cultures	add their vector of culture to the list of cultures.
]	
set list_of_cultures remove-duplicates list_of_cultures	Remove the duplicates from the resulting list
set number_of_cultures length list_of_cultures	The number of different cultures is the length of the list
end	

Table 9. Code and pseudo-code for the procedure that counts the number of cultural regions and the size of the giant component (Barelli, 2021).

Code	Pseudo-code
to find-all-components	
set number_of_cultural_regions 0	Initialize to 0 the number of cultural regions
ask turtles [set explored? False]	All the agents, until all get explored, are asked to
loop	
[	
let starting_turtle one-of turtles with [not explored?]	find a starting agent that has not been yet explored
if starting_turtle = nobody [stop]	(if no agents are left, the loop stops)
set component-size 0	Initialize to 0 the component size
ask starting_turtle [	Ask the starting agent to
explore	count its similar neighbors (recursive procedure in which the component-size counter is updated)
set number_of_cultural_regions number_of_cultural_regions + 1	Increase of 1 the number of cultural regions
]	
if component-size > giant-component-size [	If the component explored is bigger than the giant component, call its dimension the giant-component-size
set giant-component-size component-size	
]	
]	
end	

3.2. PROTON's model and simulation

The second tool used in the module has been developed within the Horizon2020 "PROTON" project (www.projectproton.eu) by a group of physicists who were commissioned to model two complex

societal phenomena: the formation of terrorist groups in European cities and the recruitment in organized crime structures (PROTON-model, 2019). At the basis of the project there is a solid research aimed to investigate the social, psychological, and economic factors leading to organized crime and terrorist networks. In the project, the authors have developed two agent-based models and simulations to account for the effects of different societal and environmental changes, as well as of policy-making strategies, on organized crime and terrorist networks. In addition to the simulation designed in NetLogo and addressed to scientists and professionals, the project has developed a user-friendly software tool called “Wizard” that embeds the results of the simulations. Indeed, the goal is making the research result available for policy makers at the international, national, and local level.
For the design of our module, we chose the model about the formation of terrorist groups. The basics of the PROTON agent-based model and of the Wizard simulator will be presented in this section.

3.2.1. The model

The terrorist recruitment model is an agent-based model with the goal to analyze which kinds of interventions reduce the risk of radicalization and recruitment to terrorism. The model is very complex, and its theoretical basis cannot be reported completely in this section. To read the model in detail the reader should refer to the report by Andrighetto and colleagues (2019). In this paragraph we emphasize the element of the model that we considered important for our implementation.
The agents in this model represent human individuals in a population which are characterized for their individual socio-demographic characteristics (like gender, age, employment status, criminal history, and authoritarian personality) and for their cultural characteristics that are based on their opinion on three topics: the perception of integration in society, the trust in institutions, the subjective condition of social advantage/disadvantage and subjective deprivation. Indeed, an accurate reading of the literature has made it possible to identify these three topics as particularly significant in the dynamics of recruitment. The socio-demographic and cultural characteristics of each agent determine its routine which, in turn, determines socialization patterns through interactions with other agents both in person and online. When the risk of radicalization reaches a certain threshold, individuals can be recruited. Recruitment in the terrorist group occurs after interacting with specific figures, the recruiters, in specific places for a specific period of time. The model measures three main outcomes: the number of individuals recruited, the number of radicalized individuals, and the cultural characteristics based on the aforementioned topics.
The time scale of the model is six months, and each phase of the model represents one hour.
The model has been initialized using the data of Neukölln, one of the most densely populated neighborhoods in Berlin. It has been chosen for three different reasons. Firstly, as a district of Berlin, there is a lot of public data available (censuses, polls, opinion polls). Secondly, numerous previous studies have investigated the type of radicalization in Neukölln, including the characteristics of places relevant to radicalization, recruitment, and counter-radicalization. Finally, Neukölln is considered to be representative of the neighborhoods in the major cities of Western Europe in

terms of urban planning, demographics and cases of radicalization and recruitment of the right, left or religious imprint.

We recall that the PROTON model aims to analyze the effect of different policy interventions on the risk of radicalization and rate of recruitment in terrorist networks. To do that, three interventions are modelled:

- Employment: employers are encouraged to hire individuals at risk of radicalization. This strategy of intervention acts at the level of the involvement of at-risk individuals in local networks made of other workers, and assumes that a job reduces the time left to radicalize and come into contact with radicalizing influences and recruiters.
- Community workers: the number of community workers operating in community centers increases. This intervention assumes that the community workers can promote positive values and opinions and hence reduce the risk of radicalization.
- Community policing: the number of specially trained community police officers increases. This intervention assumes that the involvement of this type of police offers change the role and effect of police officers in the community, reducing the number of negative interactions between citizens and police.

<u>The opinion dynamic embedded in the model</u>

In the model, the interaction between agents occurs when and where is determined by the routine activities that lead agents to converge in time and space. In addition to the spatial vicinity, the model considers the possibility of interactions among agents via online communications. The interactions make the agents' opinions change in either direction. For example, as a result of an interaction, the opinion score of trust in institution for an agent can increase (the agent becoming more trustful) or decrease (the agent becoming less trustful).

The interaction happens at the local level of agents. Every time that an agent meets another agent in the simulation in a specific location and they interact, these agents choose from a list of topics to talk about. An agent will be most likely to talk about the topic he or she feels most strongly about. The three topics which agents discuss when they interact are the aforementioned ones (trust in institutions, perception of integration in the society, and subjective deprivation).

According to the model and similarly as we have seen in the Axelrod's model, only opinions that are sufficiently similar can influence each other, and the result of the interaction is that the opinions become closer to each other.

To describe the opinion dynamics mechanism embedded in the PROTON model, graphically summarized in Figure 2, we need to distinguish between the opinions on integration and subjective deprivation, and the opinion on institutional trust. Indeed, while the first two opinions can change interacting with each agent in the system (common citizens but also special agents like community workers and recruiters), the opinion on institutional trust can be modified only through the interaction of the agents with the police.

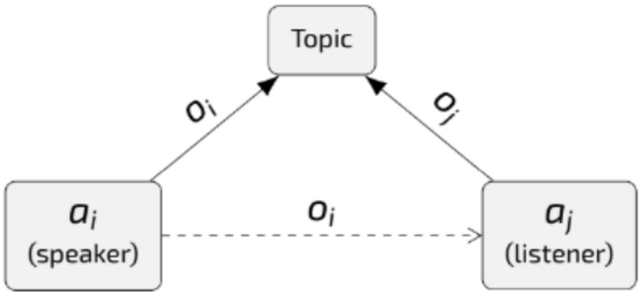


Figure 2. Schematization of the opinion dynamics in the PROTON model as reported in Andrighetto and colleagues (2019).

Each interaction is governed by the level of tolerance of each agent which is calculated as: $t_j = 1 - a|o_j|$. Interactions are classed as "successful" when the initial difference in opinions is below the level of tolerance, as indicated by: $|o_j - o_i| < t_j$. In this successful interaction, o_j's opinion is updated in the direction of o_i's to a degree dependent upon t_j as defined by: $\Delta o_j = t_j \times (o_i - o_j)/2$. This approach to update opinions therefore allows for the possibility that a successful interaction can be related to only one or two topics (namely the integration in society and the subjective deprivation).

In addition to face-to-face interactions, agents are able to interact via online communications. However, the effects of online engagement are considered about half the size as offline peers/friendship. As such, we applied the same opinion-dynamics model to online communications, whilst reducing the overall effects by half. Each agent is able to spend up to 25% of their free, leisure time using the internet, in line with the average amount of time spent on social media in Germany. As opposed to ordinary citizen agents and opinion-leader broadcasting agents, ordinary police agents have either a neutral or negative impact on citizen agents' trust/legitimacy score. Following from this, these special agents spread their opinions through the same opinion-dynamics function, albeit that instead of communicating only with a_j, they communicate with a set (either limited or unlimited) of receiving agents who each represent *aj* in parallel and simultaneously.

The changes in opinions affect the risk for the agent to be recruited by the terrorists. Indeed, the model foresee a radicalization threshold: only once an agent overcomes this level, it can be recruited if interacts with a recruiter agent. The fact that the agent can be recruited only through the interaction with a recruiter (and not with other already recruited agents) make the process of growth of the terrorist group linear and not exponential as it would be in the case if all the terrorists were "spreaders". This is a point that will be of crucial importance for the role-play activity we have designed.

Even if the basic assumption of the mechanism of interaction are the same of the Axelrod's model, we notice that in the case of PROTON a higher agents' variability is considered. For example, the Axelrod's model does not foresee that each agent has its own tolerance on a certain topic, nor that the opinion's modification happens gradually: in the Axelrod's model we had that if the interaction happens, the agent directly gets from the neighbor the exact trait for a selected feature.

3.2.2. The NetLogo simulation

The model is implemented in a NetLogo simulation, whose interface is reported in Figure 3. In the grid it is represented a bi-dimensional environment as a borough of a city which is made up of four adjacent but distinct neighborhoods. These neighborhoods differ in terms of their socio-demographic makeup (including population size), as well as the number of different places (e.g. residences, workplaces, parks, propaganda places, community centers etc.). The places in which the agents spend their time are represented in different ways in the grid, as reported in Figure 4, in which one of the four neighborhoods has been zoomed in.

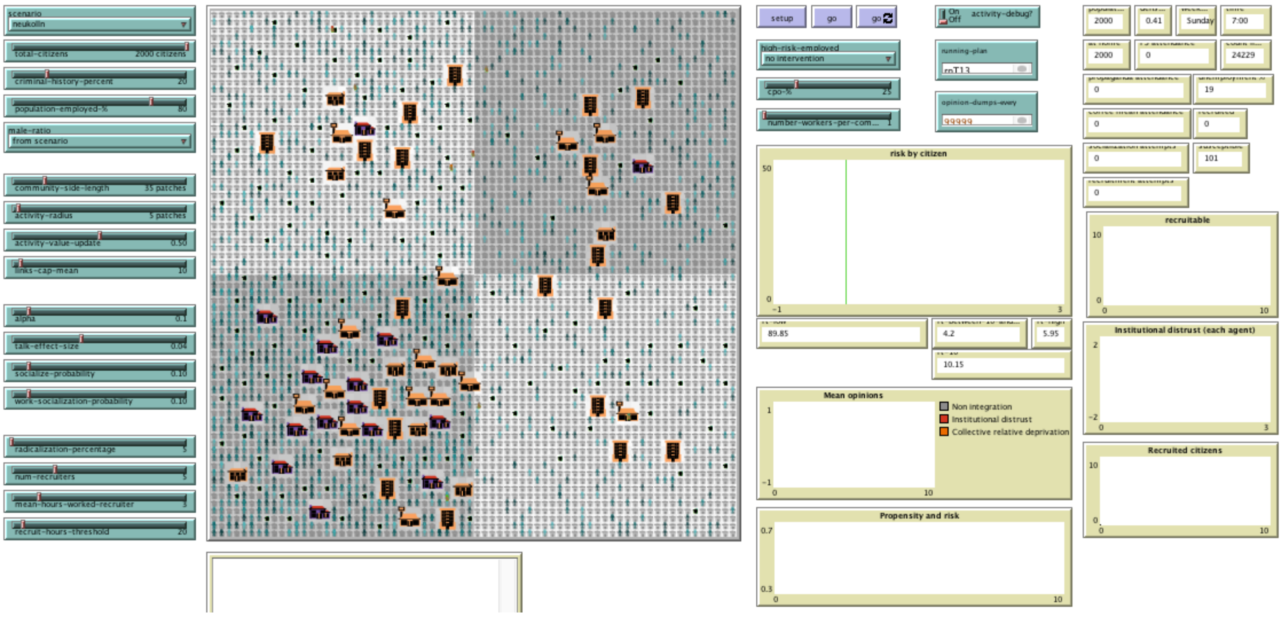


Figure 3. Interface of the NetLogo PROTON simulation.

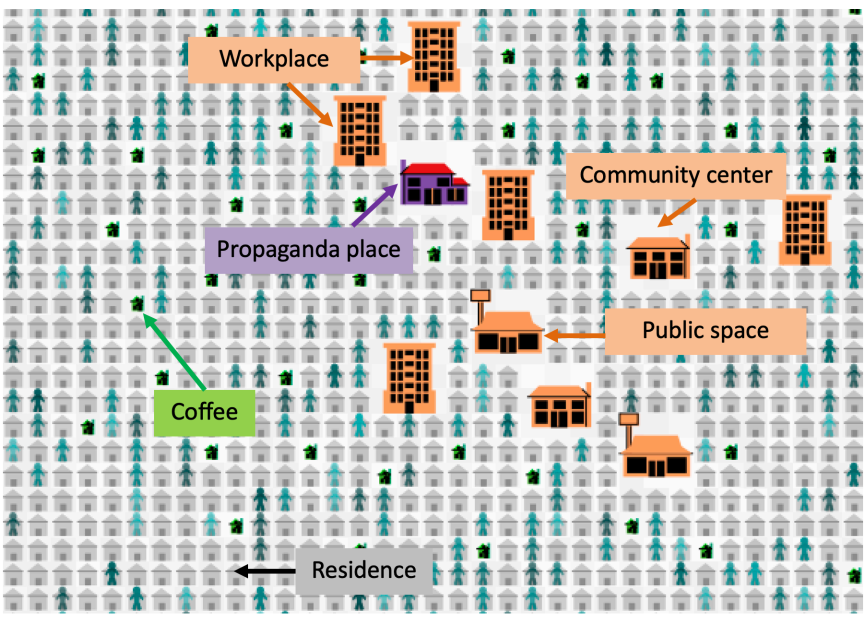
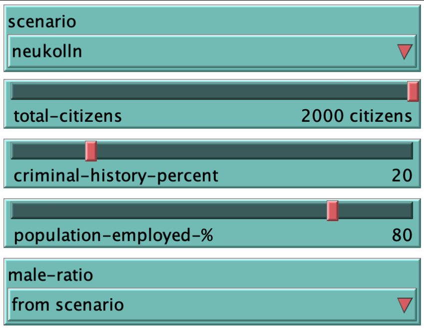
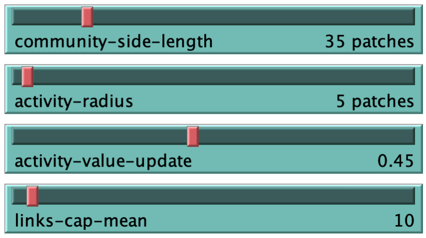
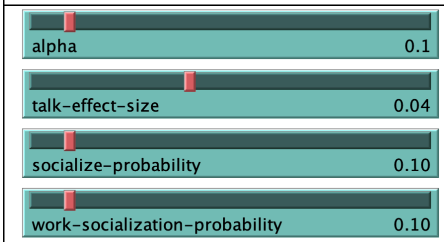
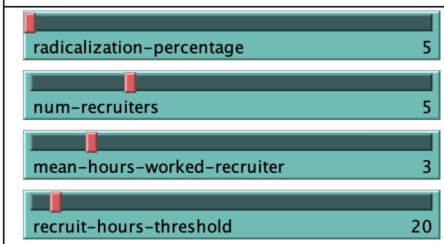
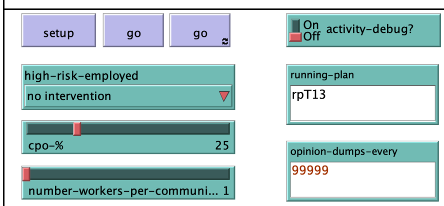
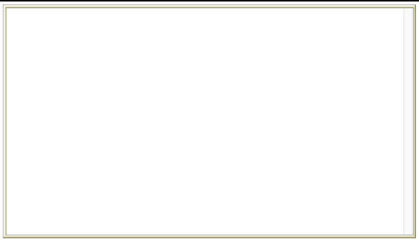
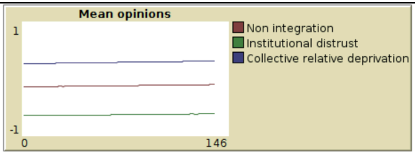


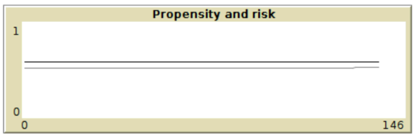
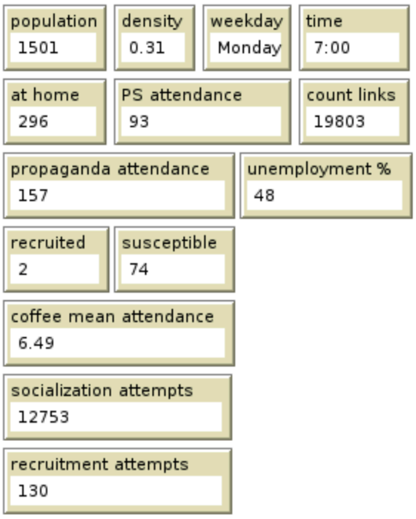
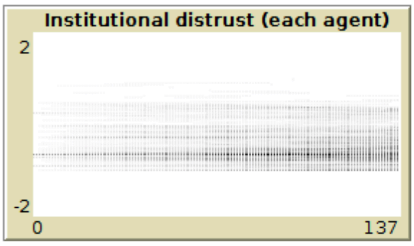
Figure 4. Representation of the simulated places.

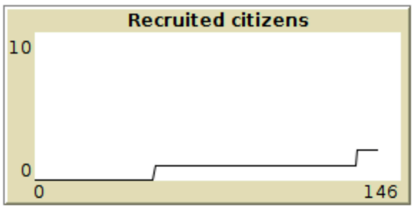
As in most NetLogo simulations, the turquoise sliders are the ones that the user can change, while the ochre sections are the spaces in which the results of the simulation run are reported. In Table 10 we provide an overview of the different parts of the simulation with which the user can interact or that can be watched to observe its evolution.

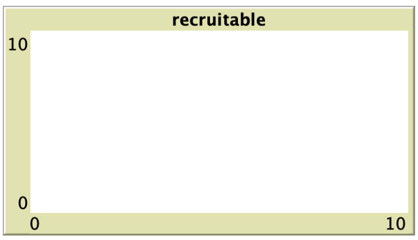
Table 10. Description of the elements of the PROTON simulation's interface as reported in (Andrighetto et al., 2019, p. 210).

Graphical element(s)	Role
	In "scenario" are specified the set of parameters to be loaded from configuration file. Currently only data from the neighborhood of Neukölln are provided. The other sliders define size (*total-citizens)* and characteristic of the population (criminals, employed, and the male-female ratio that can be loaded from the Neukölln data or forced to a specific value).
	Here it is defined the space where agents move and activities happen. *community-side-length* gives the side length of the communities and controls in turn the density of activities and citizens in the simulated space. The *radius* controls how far the agents see. *activity-value-update* weights how much a successful interaction will increase the weight of one activity (or the opposite), while *links-cap-mean* limits the number of places the agents can remember.
	Here the opinion dynamic parameters are specified. *Alpha* is the tolerance parameter, *talk-effect-size* controls how much will opinions change as a result of a successful interaction, and the two *socialize-probability* sliders control the probability of interaction at work and in leisure activities. These parameters are valid for all the agents in the system.
	Here, the recruitment process is controlled, starting by fixing the initial ratio of susceptible agents (*radicalization-percentage)* and then specifying how many recruiters we will have and how many hours they will be active, on average. The *recruit-hours-threshold* fixes, on average, the number of interactions with the recruiter that are needed before the recruitment attempt.
	This area controls simulation executions and interventions. The setup, go, and repeated go buttons are customary in NetLogo. The control below give the percentage of high-risk agents that get employed, the percentage of CPO agents (police officers especially trained) over the total police force, and the number of community workers for each community center. The large space at the bottom of the interface is used to be filled with debug information if the *activity-debug* flag is activated. It will show step-by-step activities from the recruiters agents, and some other. The *running-plan* and *opinion-dumps-every* boxes are meant to activate a routine that saves to disk individual opinions and to give it a significant name.

<table>
<tr><td></td><td></td></tr>
<tr><td>


</td><td>These plots show the position of individual opinions in the opinion space, and the mean value of propensity and risk.</td></tr>
<tr><td>
</td><td>In this set of reporters, we can read the state of the simulation. The reporters' names are mostly self-explanatory. The main result of the simulation appears here, in the number of recruited agents (recruited). The number of susceptible agents (susceptible) gives a reference on the potential recruitment pool. Coffees are the place where recruitment happens, so the mean attendance to coffee places is reported here (coffee mean attendance). Finally, the number of recruitment attempts (including contacts that happen below the necessary time threshold) together with the total number of socialization attempts, is shown (socialization attempts and recruitment attempts).</td></tr>
<tr><td>




</td><td>In the first plot is represented the distribution of agents in the opinion space in time, for just one of the topics (institutional distrust). In the second there is the number of recruited citizens over time while in the third the number of radicalized (hence, recruitable) agents.</td></tr>
</table>

If the NetLogo simulation contains, both on a graphic and on a coding level, all the elements of the PROTON model, its running is very computationally demanding. Moreover, as for all simulations of non-deterministic complex systems, the evolution of the system cannot be determined using a single run. On the opposite, an ensemble of runs is needed to reach significant results that partially overcome the unavoidable variability among the different runs due to the random events that occur in the simulation and to the intrinsic probability within the single interactions. We have said that the model has a duration of 6 month and the minimum tick of the model is an hour. This makes every run of the simulation made of 6 x 30 x 17 = 3060 steps[17]. To see the result of a given configuration, 40 runs were launched with 40000 agents each for each kind of intervention (no intervention = baseline, employment, community workers, community police). The total is of 160 simulations. Since each simulation needs about 8 days to be completed, it means that 1280 computation hours are needed (more than 53 days).
Of course, even if we could overcome the potential difficulties in managing the NetLogo simulation and its interface, this amount of time to obtain the result makes this simulation definitely out of reach for a non-specialized user. That is why the researchers of the PROTON project developed a software tool to visualize the main results of the simulation. We present the PROTON-Wizard tool in the next paragraph.

3.2.3. The PROTON-Wizard simulator

The PROTON-Wizard has been created for a user-friendly visualization of the results of PROTON simulation models (Kotowski, Jasik & Taberski, 2019). This tool enables the non-expert users to configure, visualize and compare the results of simulations without actually having to run these simulations but using the results of previously obtained calculations. Because of this, it is mainly targeted to policymakers. The PROTON-Wizard (PROTON-Wizard, 2021) has been developed both for the model on organized crime and for that on terrorist networks. We will focus only on that about terrorist networks.

The interface

After choosing one of the three interventions, the user sees an interface like that reported in Figure 5. The data obtained in the scenario specified are presented in two horizontally separated sections. At the top, there is a table and a chart, both of which present data concerning recruited citizens or the risk of radicalization compared to the baseline scenario in which no policies have been implemented. At the bottom, there is a graph showing the data concerning the average opinions in the population about the three topics of perception of integration in the society, trust toward institutions and the subject feeling of deprivation; even in this case, the data can be compared with the baseline scenario. Differently than in the section above, in the plots for the opinions, can be studied the four neighborhoods separately.

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[17] In the model, months of 30 days and days of 17 “active” hours are considered, assuming that during nighttime nothing happens.

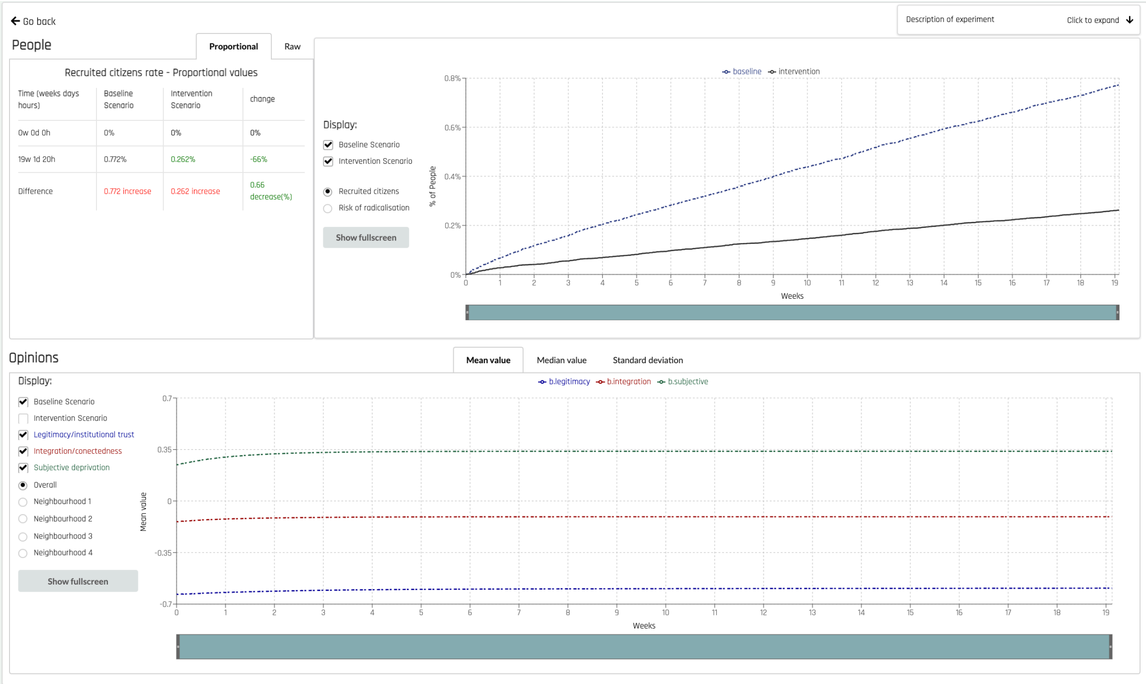


Figure 5. Interface of the PROTON-Wizard (2021).

The users of the PROTON-Wizard not only can explore the results of the prototypical city (Neukölln) but can also customize an environment based choosing parameters like the gender ratio, the unemployment rate of the population and the percentage of citizens with criminal history and adapting the different interventions.

<u>The results</u>

The PROTON-Wizard allows to visualize the results of them implementation of the three types of intervention with respect to the business-as-usual scenario. In Figure 6, 7 and 8, we report respectively the graphs for the recruited citizens, risk of radicalization and opinions for the three strategies of intervention.

In the case of employment strategy, while the average radicalization was similar to the base model, large and strongly statistically significant differences were found in the number of recruited agents. In total, the experiment reduced the number of recruited individuals from about 77 to about 26, or a 66% reduction compared to the based model.

In the scenario with community workers, there were no statistically significant differences compared to the baseline in terms of recruited agents but the mean risk of radicalization of the populations were statistically different. These differences are likely the result of the fact that the experiment also had statistically significant effects on improving all three opinion related factors. Accordingly, the community worker model has meaningful impacts on attitudes in the simulated city, but those differences did not lead within the 6-month observation period to significant changes in recruitment.

In the last scenario with community policing there were no statistically significant differences in the recruited agents and in the risk of radicalization. However, the experiment did have statistically significant effects on improving the trust in the institutions.

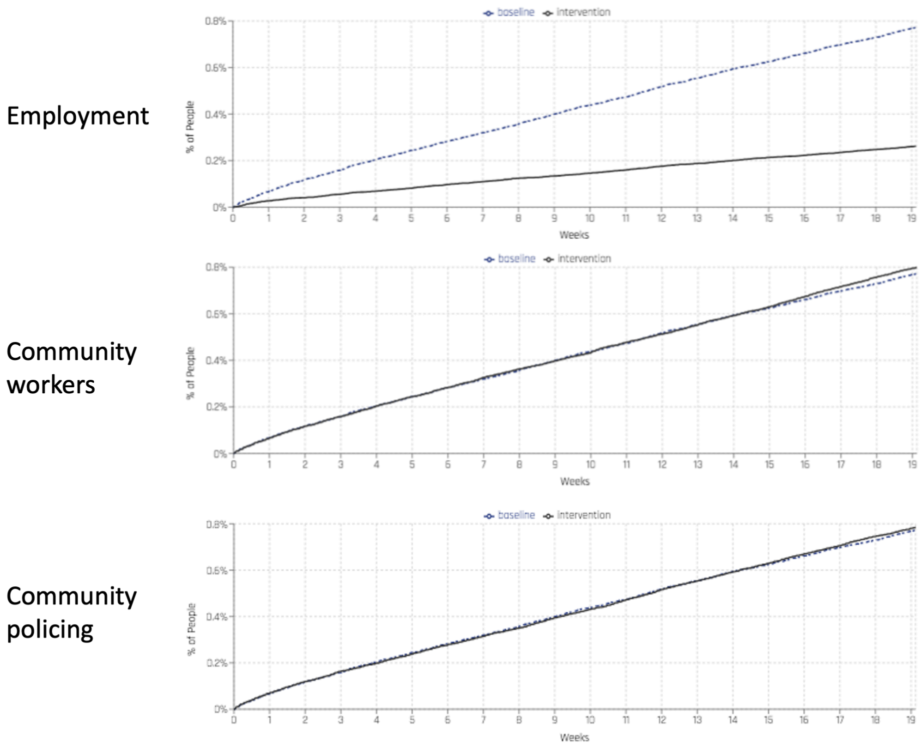


Figure 6. Plots for the percentages of recruited people over time in the three intervention scenarios compared to the baseline.

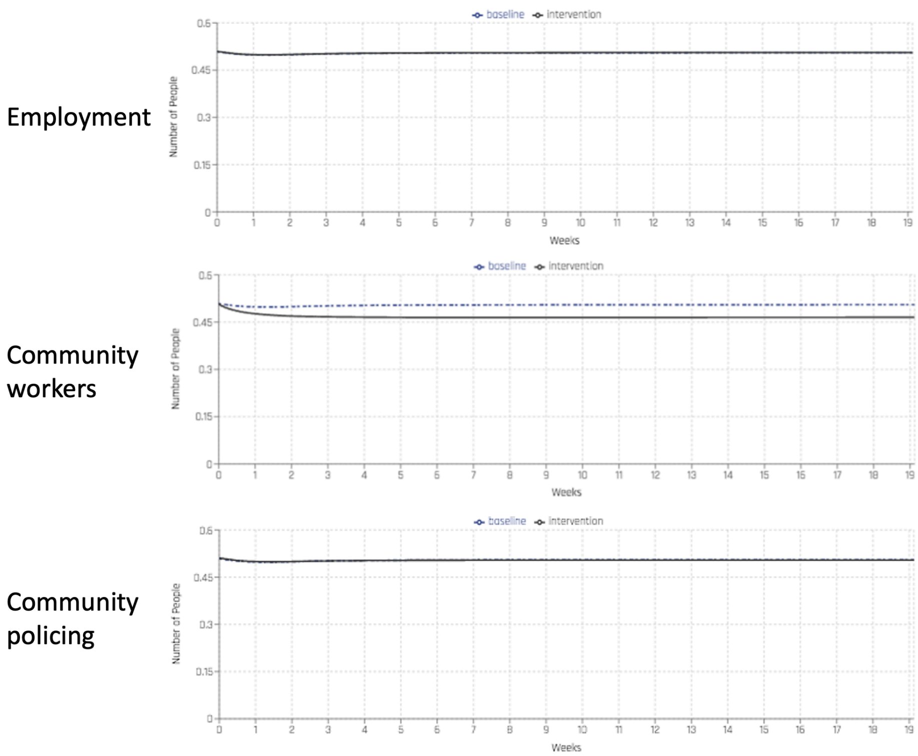


Figure 7. Plots for the risk of radicalization over time in the three intervention scenarios compared to the baseline.

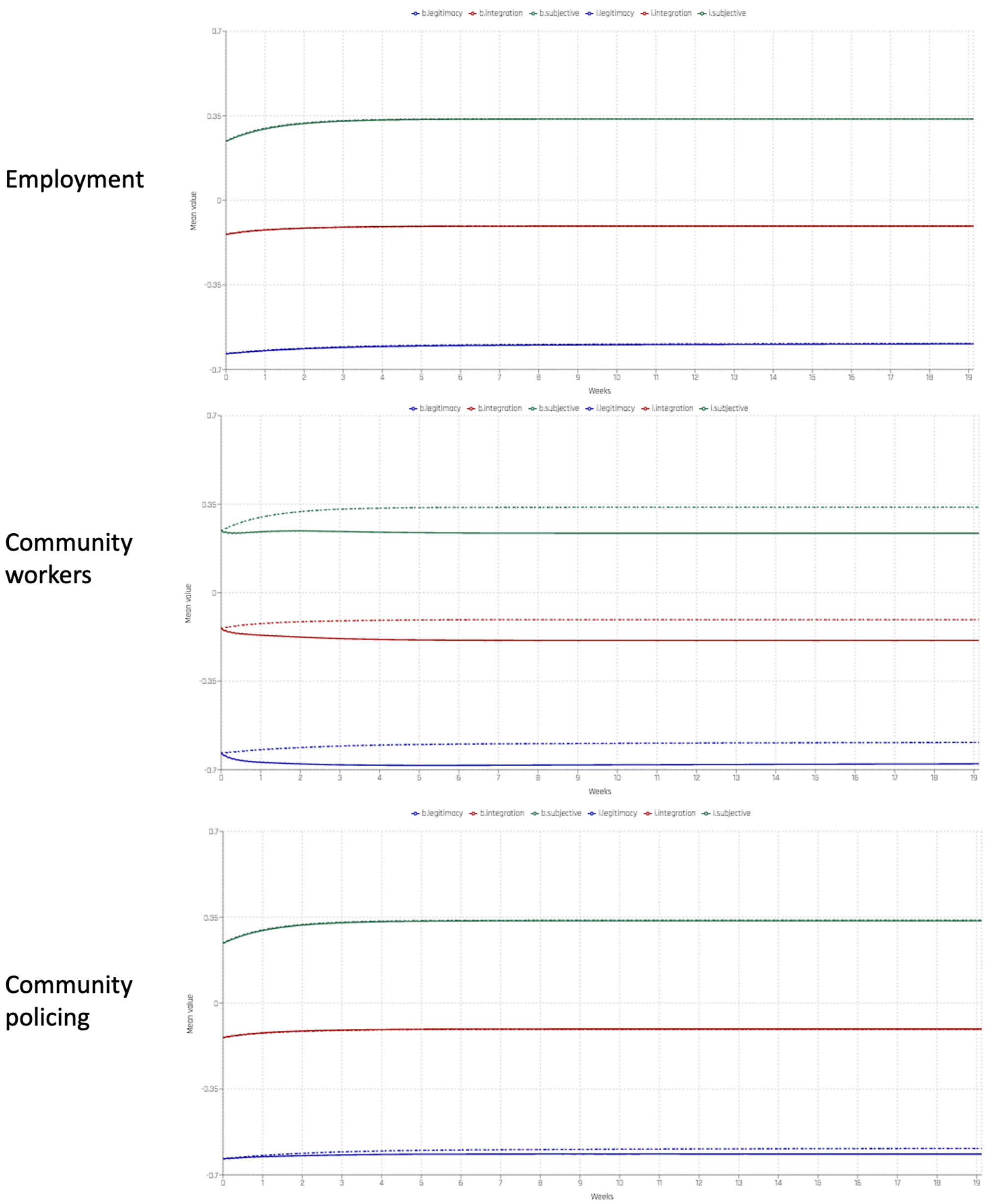


Figure 8. Plots for the average opinions about the topics of subjective deprivation (green, top), perception of integration (red, middle) and institutional trust (blue, bottom) over time in the three intervention scenarios compared to the baseline.

In conclusion, the researchers of the PROTON project discovered that only the employment strategy had a statistically significant effect on recruitment (Andrighetto et al., 2019). On the other side, it had no significant effects on radicalization or on any of the opinion-related factors. On the other hand, the community workers' scenario showed a significant effect on the mean risk of radicalization of the population as well as on improving in general the opinions on the three topics. The community policing policy improved overall trust and legitimacy but had no significant effect on any of the other outcomes.

4. The background of the study: preliminary interviews

The tools presented in the previous section, the Axelrod's NetLogo simulation and the PROTON-Wizard, were the basis for the design of a protocol for individual interviews with university Physics and Mathematics students who attended a course on Physics Teaching at the University of Bologna. The goal of the interview was studying how the students deal with models and simulations of a social complex problem, i.e. the formation of a terrorist group in a city. To facilitate the interviewees' immersion in the problem described, the whole interview is conducted as the interviewee was the mayor of the town in question, who is faced with a real emergency. The protocol is then divided into four sections:

1. formulation of the problem and preliminary analysis: to the students was shown a graph with the temporal evolution of the number of people belonging to the terrorist group (one of the baseline plots in Figure X);
2. exploration and discussion of the expert model on recruitment: to the students were presented the basics of the PROTON agent-based model (the characteristics of the agents, the relevant opinions, the role of the routine);
3. analysis of a specific problem on opinion dynamics within the expert model: to the students was introduced the Axelrod NetLogo simulation to understand the mechanisms at the basis of the exchange of opinions which is in turn at the basis of the recruitment dynamics in the PROTON model;
4. exploration of three policy scenarios through the simulation: the PROTON-Wizard was shown to the students to see the effects of the different interventions on the number of recruited agents and on the opinions on the three sensitive topics.

In the end, a space was left for final comments from the students about the role of simulations to address societal problems.

The protocol was firstly validated with two researchers of the PROTON Project (Prof. Mario Paolucci and Dr. Daniele Vilone, CNR Roma) in order to verify its scientific robustness. Then, it was piloted with a Ph.D. student in the field of Physics Education to test the quality and intelligibility of the questions. The final version of the protocol, available in the Appendix A, was then used to conduct, between March and April 2020, eight semi-structured online interviews with university Physics and Mathematics students.

During the interviews, emerged in the students a profound appreciation of the activity. Indeed, they said that the interview was a "one-hour space" to reflect on issues that they felt particularly relevant in a very challenging period for them (from March to May 2020, Italy, as many other countries, was in total lockdown). The students' positive feedbacks on the interviews made us plan a series of lectures and activities for all the students attending the course of Physics Education. In particular, the eight interviewees took actively part in the process of adaptation of the individual interview they had experienced in a focus group activity that they proposed to design as a role-play activity. In the following section we describe the resulting module with the activities implemented.

5. The module on agent-based simulations

The module on agent-based simulations was conducted remotely in April 2020 during Italian COVID-19 lockdown. The participants were 50 university Physics and Mathematics students enrolled in a course of Physics Education at the University of Bologna. The module, 7 hours in total, was structured in three parts.

It started with a 2-hours lecture on the differences between simulations in education and in the scientific practice in the light of the ongoing pandemic; the case study of the SIR model was presented to highlight the difference between the two main approaches to simulations: the equation-based and the agent-based ones.

The next phase consisted in a 2-hours focus group activity. The 50 students were divided in 8 groups and each group had as facilitator one of the eight interviewees. The activity consisted in the analysis of the Axelrod's NetLogo simulation.

The last step was another 2-hours group activity structured as a role-play activity in which the students, in the same groups and guided by the same facilitators, had to analyze the problem of the terrorist group formation using different elements of the PROTON model and simulation.

In the next paragraphs we will analyze in detail the two focus group activities.

5.1. The focus group on Axelrod

The lecture on simulations that preceded the group activity ended assigning to the students the tasks to download NetLogo on their devices, read the information sheet of the Axelrod's simulation (Barelli, 2021) and do some preliminary tests to get familiar with the main rules of the model. The focus group was then aimed at analyzing the emergent phenomena displayed by the simulation. Indeed, most of the questions required an explanation of global configuration of the system based on the local mechanisms of interaction. As we presented in the section about the Axelrod's model, for each of this behavior it is possible to formulate a mechanistic explanation that relies on the model's assumptions and rules and arrives to the observed phenomenon. Other sections of the protocol were oriented to make the students discuss on the passage from the model to the real-world issues that can reflect the simulated phenomena. In the end, the students were asked to recognize the Axelrod's as an example of agent-based model of a complex system. In Table 11 are reported the questions of the protocol that the facilitators used to guide the focus-group activity flanked by the goals of each question.

Table 11. Protocol of the focus group activity on the Axelrod's simulation. On the right column we report the questions, on the left their objectives.

Question	Objectives of the question
Part 1: Explaining the simulation	
The dynamics of the simulation lead to the formation of one or more cultural regions, which we can define as a set of adjacent agents with the same culture (same traits for all cultural characteristics). Does the	Guide the students to explain the phenomenon of formation of stable cultural regions, connecting it to the rules of the simulation.

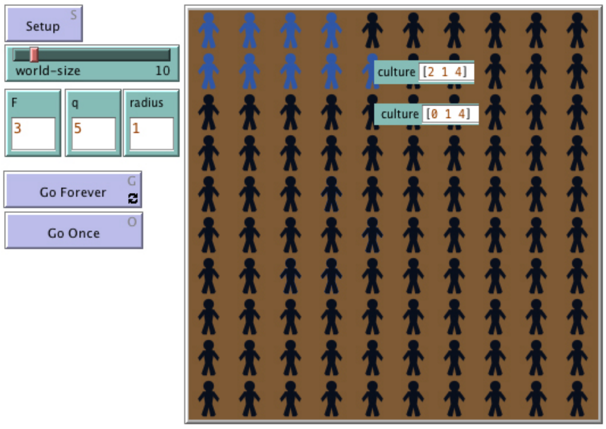
occurrence of this phenomenon seem reasonable to you? What rules of how the simulation works allow you to tell?	
Sometimes the simulation leads to the achievement of situations of cultural homogeneity, but at other times it causes culturally distinct regions to develop. How do you explain this last phenomenon? Do you see a contradiction between this polarization phenomenon and the basic rules of the model?	Guide the students to observe that different collective evolutions (polarization and convergence) are possible for the system. Guide the students to explain the phenomenon of polarization based on the rules of the model. Guide the students to recognize the apparent contradiction between the local rules of the model and the emergent phenomenon of polarization.
It may happen that as the simulation progresses, two cultural regions of agents are formed that differ from each other only for one characteristic, as shown in the figure:  Can you imagine an evolution of the system starting from this intermediate configuration? How do you explain the evolution you expect?	Guide the students to observe that, when in the system two similar cultures survive (dialects), the most probable evolution is that in which the group with more agents eats the other ("majority eats minority"). Guide the students to explain this evolution through probabilistic reasonings grounded in the basic rules for the agents' interactions.
By varying the number of cultural characteristics F and keeping the other parameters constant, you should observe that the probability of obtaining a single cultural region increases. Why does this happen? Instead, by increasing the number of traits q and keeping the other parameters constant, you should observe that the probability of obtaining more distinct cultural regions increases. Why does this happen? By increasing the range of interaction, always keeping the other parameters constant, you are more likely to observe the formation of a single cultural region. Why does this happen? The last parameter that can be changed is the number of agents, using the world-size slider. What happens by changing it? What behaviors do you observe? How do you explain them to you?	Guide the students to observe the different behaviors that can be obtained when changing the four parameters of the simulation: - The number of cultural features (F) - The traits that can have each feature (q) - The range of agents' interaction (radius) - The number of agents (world-size) Guide the students to explain these behaviors on the basis of the rules of the model.
Keeping the parameters F, q and radius constant, varying only the number of agents, we can observe a graph of this type for the average number of cultural regions at the end of the simulation:	Guide the students to observe the variability of the number of cultural regions depending on the number of agents in the system. Guide the students to explain this unexpected behavior on the basis of the rules of the model.

 **Figure 2: Average Number of Stable Regions** NOTE: The parameters for these runs are five cultural features, 15 traits per feature, and four neighbors for interior sites. Each territory size was replicated 40 times, except the territories with 50 × 50 sites and 100 × 100 sites territories, which were replicated 10 times. Small and very large territories result in a small number of cultural regions, while medium-sized territories lead to the largest number of cultural regions. Why does this happen?	
Part 2) Interpreting the simulation	
For each of the above questions, can you think of one or more social situations that mirror, recall, or exemplify the simulated phenomena?	Invite the students to find examples of social situations that they associate to what they have experienced in the simulation. Guide the students to move from the world modelled in the simulation to the real-world phenomena.
Part 3) Recognizing the Axelrod's model as an example of agent-based model of a complex system	
In conclusion, can it be said that the Axelrod model models a complex system? Why?	Make the students reflect on the complexity reflected in the Axelrod model.
This simulation shows an example of agent modeling. In which parts of the simulation is this evident (interface, code, ...)?	Guide the students to recognize in the simulation the features that make it an agent-based simulations.
The model shows that simple rules of convergence can give rise to counter-intuitive and unexpected aggregate phenomena. Can simulation help make them more reasonable?	Guide the students to discuss the potential of computational simulations to explain and make sense of complex, unexpected and counter-intuitive phenomena.
What limits and advantages can it have to model a range of social phenomena in this way?	Make the students aware of the limits and advantages of agent-based modelling and simulations to address societal problems.

5.2. The role-playing activity on terrorism

The focus group activity on the formation of terrorist group was designed together with the 8 interviewees on the basis of the protocol used for the individual interview. Since in the interview the students were required to imagine to be the mayor of a town shocked by the terrorism emergency, the interviewees themselves proposed to transform the activity in a role play. In this activity they imagined there was a mayor who acted as the facilitator of the discussion and other members of the city council who had to support the mayor facing the emergency. Since the groups were between 6 and 8 students each, 7 characters were constructed: 1 public order responsible, 1 social integration advisor, 1 tourism, culture and events advisor, 1 urban planning advisor, 1 scientific development advisor, 2 councilors. In Appendix B, we report the description of the roles that were sent to each participant before the beginning of the game. The descriptions of the roles have a similar structure: in the first part, there is a professional and personal description of the character as well as the role they have in the city council; in the second, there is a piece of information that regards the character about the current situation of the city.

The goal of the role-play activity was guiding the students to reason on the problem of the formation of terrorist networks by proposing them different elements of a scientific simulation. Indeed, in the PROTON-Wizard and in the related model we recognized a variety of representation forms of the modelling knowledge and for the activity we tried to unpack them to see how the different elements were used by the students in their reasoning on the problem. Specifically, we progressively proposed to the students:

1. A statement of a phenomenon, i.e. the formation of a terrorist group in town;
2. A graph with the evolution of the number of people in the terrorist group in the five previous months;
3. Three alternative possible interventions that are the basis for the realization of different scenarios;
4. The features of the agent-based model that can be formulated to construct a simulation.

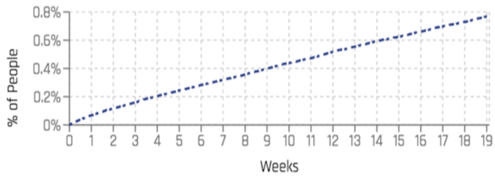
At the end of the role-play, after the students had decided what in their opinion was the best intervention to realize, the last two element were introduced:

5. The results of the simulation run (using the PROTON-Wizard software) and relative graphs;
6. The interface of the PROTON NetLogo simulation and elements of the code.

With this idea of unpacking elements of the model and the simulation to make the students progressively focus on them, the role-play activity was articulated in four phases, detailed in Table 12. In each phase a new element of the PROTON-Wizard simulation was unveiled by the master to the students (statement, graph, actions and scenarios, model). The group was requested to negotiate a decision for an intervention to contrast the formation and increase of the terrorist group.

Table 12. Phases of the role-play activity, pieces of information given and prospected goals.

	Role-play protocol	Piece of information	Goal
Statement	"I have just received this file from Xitta's Secret Services: *CLASSIFIED INFORMATION: A terrorist group has recently formed in our town and appears to be expanding. In five months, the group has grown nearly to 200 people. You may wonder how it happened, what the reasons are, what order of magnitude it is. We will continue to investigate, considering that we have never encountered such movements in the city until now. That's all for now.* What do you think? How could it happen?"	Claim of existence of a phenomenon, i.e. the presence of a terrorist group of 200 people in Xitta	To introduce the phenomenon and stimulate an initial brainstorming about the origin of the claimed phenomenon

Graph	"I have just received another message with a file containing data on the trend of the number of people in this terrorist group. You have to help me to interpret it. Beyond the reasons for "why" a terrorist group was formed, can you see a mechanism with which this was formed? Can you see a "story" of this group?" 	Data represented with a linear graph for the percentage of recruited people (with respect to the population of the town) over weeks (PROTON-Wizard, 2020)	To check if students were able to recognize a recruitment mechanism from the linearity of the graph, in particular if they were able to exclude a virus-like "Chinese-whisper" process, which would lead to an exponential trend
Actions and scenarios	"We are offered these types of intervention to deal with the emergency. We can i) increase the number of specially trained community police officers, ii) increase the number of social workers, iii) incentivize employers to hire individuals at risk. What would you recommend me to do?"	Details about the policy interventions for which the PROTON developed the simulation (Andrighetto et al., 2019)	To engage students in discussing the scenarios to which the different policy interventions would have led, and to evaluate their potential effectiveness on the basis of the previous hypotheses on the recruitment mechanism. To make the discussion more articulated and make argumentation mor explicit, a random character is secretly corrupted by the terrorist group and is required to advocate against the most voted decision.
Model	"Researchers who model complex social phenomena want to present us a work they conducted on our problem. This is the first part of the report, which describes the model they used to realize a computational simulation. […] On the basis of this model, what final decision do we want to make? What intervention are we going to select?"	Details about the agent-based model at the basis of the simulation: model of agents, opinion dynamics, routines (Andrighetto et al., 2019)	To check if students were able to use Axelrod's model of opinion dynamics to interpret the model of terrorist group formation, and to use the given model to evaluate the possible actions and scenarios in order to make a final decision

The guide for the role-play activity used by the facilitators (who played the roles of mayors in their groups) in reported in Appendix C. In this guide, co-constructed with the facilitators themselves during several sessions of design, training and preparation, the questions are flanked by notes with the objectives that the group should reach in each phase, prompt for discussion in case of divergence from the objective and other useful tips.

Before the realization of the role play with the 50 students, the activity was piloted with a group of 7 Ph.D. students. During this session, one of the facilitators played the role of the mayor and the others assisted silently.

7. Research Questions

Of the activities proposed to the students in the module, for this chapter we focus on the role-play one and analyze data to answer the following research questions:

RQ1. Which forms of reasoning do students put into play when discussing a complex societal problem through a simulation?

RQ2. In particular, which forms of reasoning are triggered by different elements of the simulation (data, graph, actions and scenarios, model)?

How the research questions were obtained will be explored in detail in the methodological section.

8. Methodology of data analysis

For the data analysis of this study, we considered as data corpus the video-recordings of the role-play activity of the eight groups. The analysis was articulated in the following phases:

1. Debriefing, identification of the macro-phenomenon and formulation of the research questions

After the implementation of the activity, debriefing activities were carried out with the members of the research group who had observed the role-play activities while taking place. In these meetings, the notes of the researchers were used alongside the video-recordings of the activity. The debriefing meetings allowed to point out a macro-phenomenon that seemed to emerge from data. It consisted in the identification of a relationship between two elements: on one side, the phase of the game that was connected to the kind of scientific information presented to the students (a statement, a graph, a scenario, a model, or a simulation) and, on the other, the students' attitudes toward the problem, their ways of reasoning and discussing. For example, students seemed to struggle focusing on the mechanism of formation of terrorist groups, even though the master/facilitator often called attention to this aspect; moreover, a source of scientific information like the linear graph, that was supposed to trigger in the students a focused reasoning on the mechanism of interaction, did not activate this kind of reflections.

A preliminary research question was then sketched: *How does the type of scientific information trigger in the students the activation of different forms of reasoning about a complex social problem?* This research question was chosen according to three criteria. Firstly, it captured an emergent phenomenon that was "in the air" and the debriefing meetings had clearly pointed out. Secondly, it provided an analytical lens through which look at the data (the different forms of reasoning and the connection with the phases of the activity). Finally, it also suggested a synthetic lens to go beyond the surface of data and provide a new contribution to the research field. When the analysis progressed, to better present the results we realized that it was convenient to unpack the research question in two separate parts: one about the different forms of reasoning and another about the relationship between the activated forms of reasoning and the kind of scientific information presented.

2. Data organization and bottom-up coding

After having identified the research questions, the data had to be prepared for the coding phase. Hence, the video-recordings of two groups (one-hour-and-a-half each) were transcribed and anonymized using pseudonyms in which the only reference kept is to students' gender.
The preliminary analysis was conducted on one of the two groups in a bottom-up way to identify categories for the students' forms of reasoning. When a stable set of codes was identified, the analytical lenses were applied to the rest of the data corpus, always keeping the possibility open to add or modify categories.
Concretely, we constructed the analysis in an Excel file that reported in the rows the chronological order of students' speeches. If, in a single speech of a single student, more than one code could be identified, it was split in two or more rows in order to have each line coded with only one label. For each line, an automatic function was used to count the words in that specific line. A color code was used to highlight sentences coded with the same category. In Figure 9 we report an example of coding of some lines and of the database organization.

Role	Transcript	Number of words	Coding
Scientific development	No, certainly not... But was another message sent by the secret services or do we still have that?	18	
Master	for now we have this ... If maybe you can explain me a story of how this group was formed. I need to know a story. That is, how did they get in touch to expand, in your opinion? Who wants to speak.	43	Causes: mechanism
Councilor	In my opinion there must have been a triggering event that caused discontent among several people	16	Causes: trigger event
Councilor	and from one person, two people will have come up with the idea of actively acting by doing something, and people around him will have started to gather.	28	Causes: mechanism
Master	And how? That is, according to you, Miss Laura, how they gathered,	12	Causes: mechanism
Master	Where is it? Because here we have an expert in urban planning who could also tell us where, how ... There are squares ...	24	Context: places
Urban planning advisor	What I can say and the assumption I can make is that as you said a socio-economic mapping ... [interruption] I was saying that trying to put together what has been said, having the socio-economic mapping of the neighborhoods of the city, we collected this mapping by conducting a survey that revealed precisely that one of the major meeting places is this peripheral area.	64	Context: places
Urban planning advisor	I do not remember well if it was Laura, the city councilor, who had said that she still lived and perhaps lives, or in any case she has to do with people who live in the peripheral area and she felt that there is strong discontent ... we could find a localized origin not in a square in the city center but rather in an area where strong migratory flows or large agglomerations are concentrating.	75	Causes: problematic places
Councilor	I agree	2	

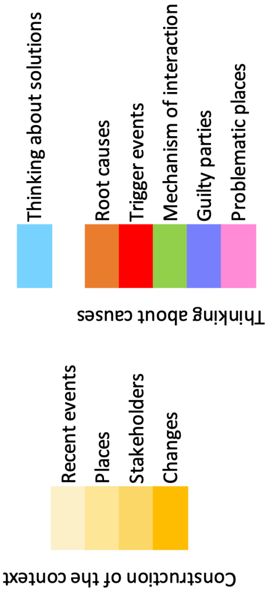


Figure 9. Structure of the file used to code the transcript. On the right, color codes for the different categories of students' forms of reasoning.

3. Weighting and contextualization of codes

To answer the second research question, we needed a form of organization of the database that allowed to:
- monitor the parts of transcript that could be coded with the categories pointed out and other more discursive parts;
- see distribution of the codes in the overall structure of the transcript and in the different sections of the role-play activity;

- appreciate the contribution of each student to the discussion;
- distinguish between long and short speeches coded with the same label.

To do that, the database as reported in Figure 9 was re-structured reaching the form reported in Figure 10. Here, the rows still report students' sentences in a chronological order, but they were dislocated in different columns depending on who pronounced the specific sentence. Other rows were added to signal the phases of the role-play activity. The height of the rows was adjusted through an automatic function proportionally to the number of words in each row. The color code to indicate the categories of students' forms of reasoning was maintained the same as Figure 9.

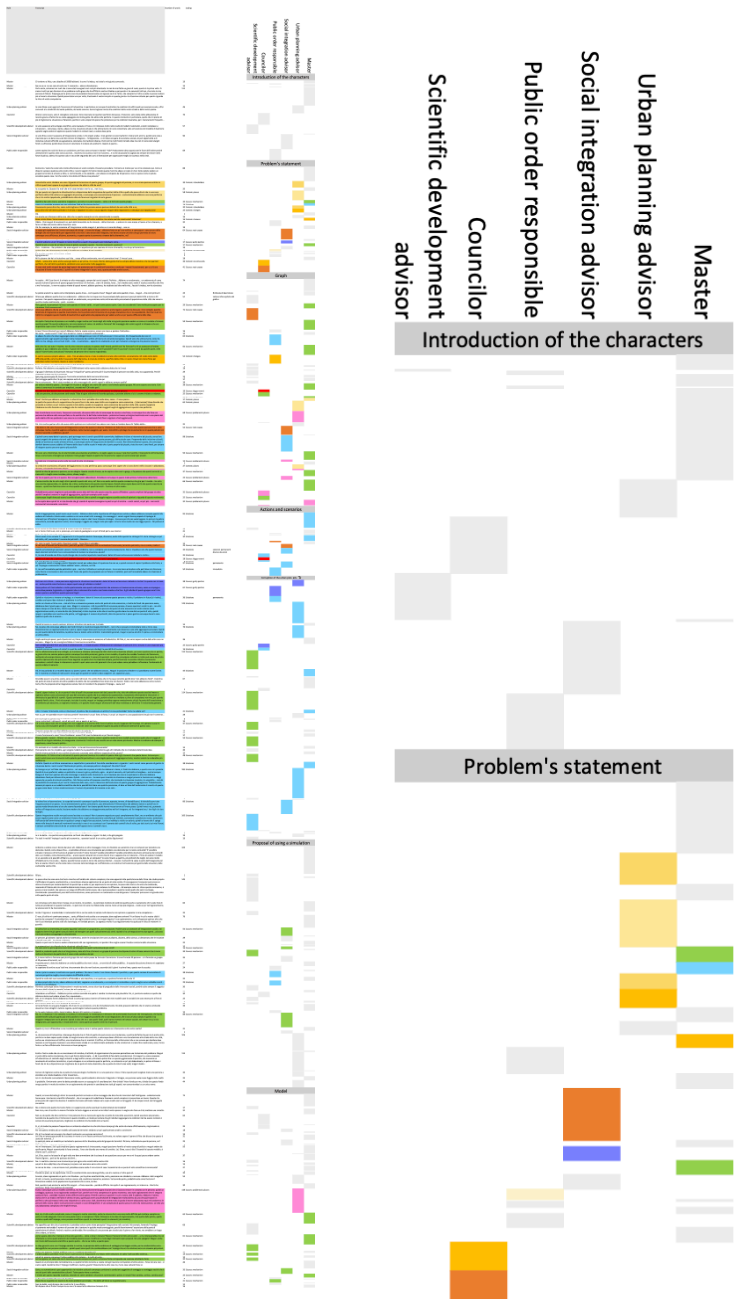


Figure 10. On the left, final structure of the database. On the right, a zoom in on the initial parts of the role-play activity.

9. Data analysis and results

We divide this section in two parts, each of them provides a contribution to answer one of the two research questions.

9.1. The forms of reasoning activated by the students in the role-play activity

To respond to the first research questions, students' reasonings were clustered according to three macro-categories: i) construction of the context, ii) thinking about solutions and iii) thinking about causes. Data analysis allowed these macro-categories to be articulated, as summarized in Table 13.

Table 13. Macro-categories of students' forms of reasoning within the role-play activity and examples of students' sentences.

Construction of the context	
(recent events)	*I wanted to say that lately a wave of vandalism has occurred in the city*
(places)	*If we think about the hypothesis of the agglomeration in the peripheral area, I can still let you know that there are several abandoned buildings that were left, let's say, by companies that have closed*
(stakeholders)	*There are still families who do not have equal opportunities and who are not yet well integrated, do not yet have a job*
(changes)	*In the last period the area has been repopulated due to the immigration of a group of people… a repopulation of the neighborhood occurred*
Thinking about solutions	
We have to start integrating these people, starting from small things. By proposing cultural initiatives, giving at least basic social assistance, or in any case also integrating children in schools	
Thinking about causes	
(root causes)	*Apparently, there was an external input, or something linked to what my colleagues said, some migration phenomena or some discontent, which led to the formation of the group*
(trigger events)	*In my opinion there must have been a triggering event that caused discontent among several people*
(mechanism of interaction)	*In my opinion there must have been a triggering event that has caused discontent between several people… and one person, maybe two people had the idea of acting, doing something… then others started to gather around them*
(guilty parties)	*Regarding the formation of this group, of this aggregate of people, do you know if they have entered the city in recent months or is it a group of people who have lived in the city for years?*
(problematic places)	*We could find an origin not in a square in the city centre but in an area where there are strong migratory flows or strong agglomerations*

The first macro-category includes forms of reasoning activated to search for elements of the context to construct the setting where the problem is framed. In particular, these forms of reasoning include sharing pieces of information received when their roles have been assigned to them, or make hypothesis about the missing details. The macro-category named "construction of the context" has been articulated in four sub-categories ("recent events", "places", "stakeholders" and "changes"), depending on the elements taken into account.

The second macro-category refers to students reasonings activated for thinking of *possible solutions* for the phenomenon of formation of terrorist group.
The third macro-category includes students' reasonings about *causes*, which were detailed in four sub-categories. The first sub-category refers to root causes of the phenomenon, usually referred as social problems of discontent and tension. As opposed to see the causes in profound societal phenomena, there is also a form of reasoning that emphasizes the role of triggering events in producing the observed problem. A different type of cause focuses on the mechanism of interaction among individuals, how they communicate and how they have contacts and exchange opinions. Another sub-category regards the search of guilty parties, groups of people that are considered dangerous and responsible for the terrorist group formation. The last sub-category refers to the presence of slums or problematic places in general.

9.2. The relationship between the forms of reasoning activated and the type of scientific information made available

To answer the second research question, the categories presented in Table 13 were used to code two groups' transcripts as reported in Figure 11 and 12.

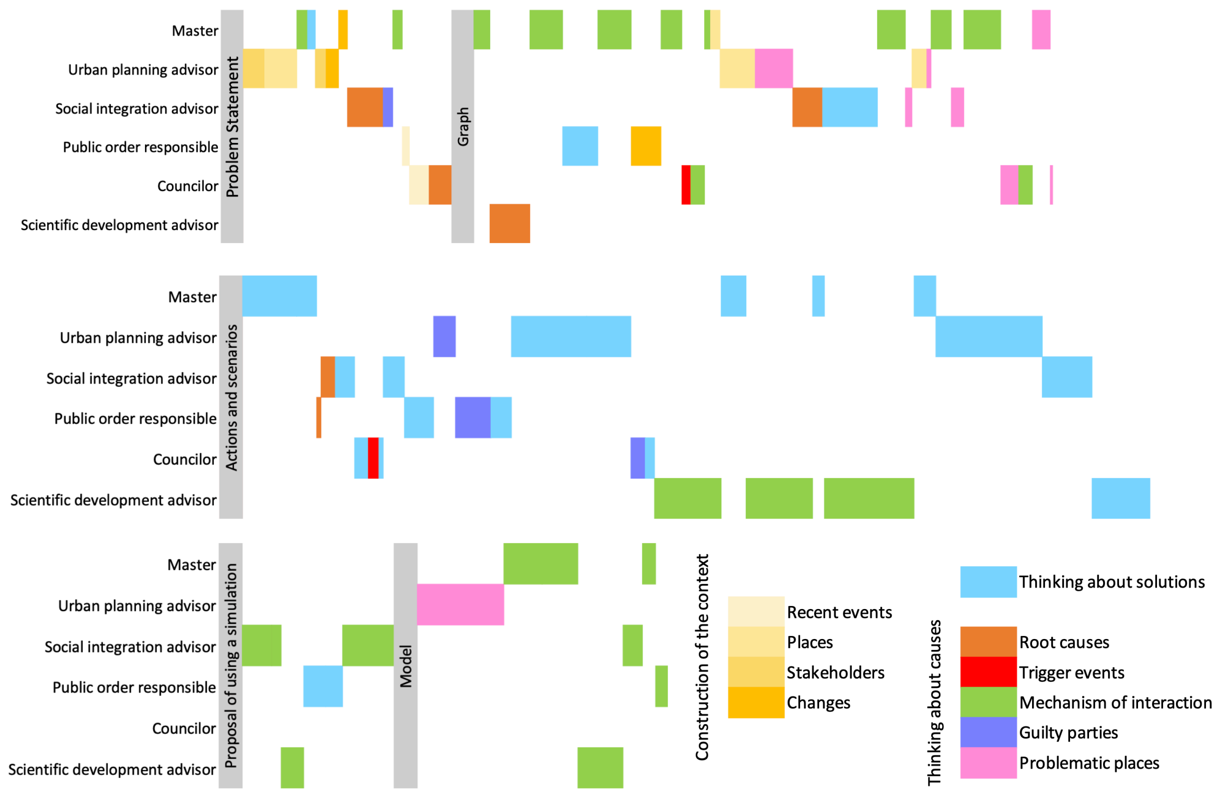


Figure 11. Coding of the group 1's discussion during the phases of the role-playing activity using the markers for i) construction of the context; ii) thinking about solutions; iii) thinking about causes. The length of the bars refers to the number of words coded with a given code in the specific piece of transcript.

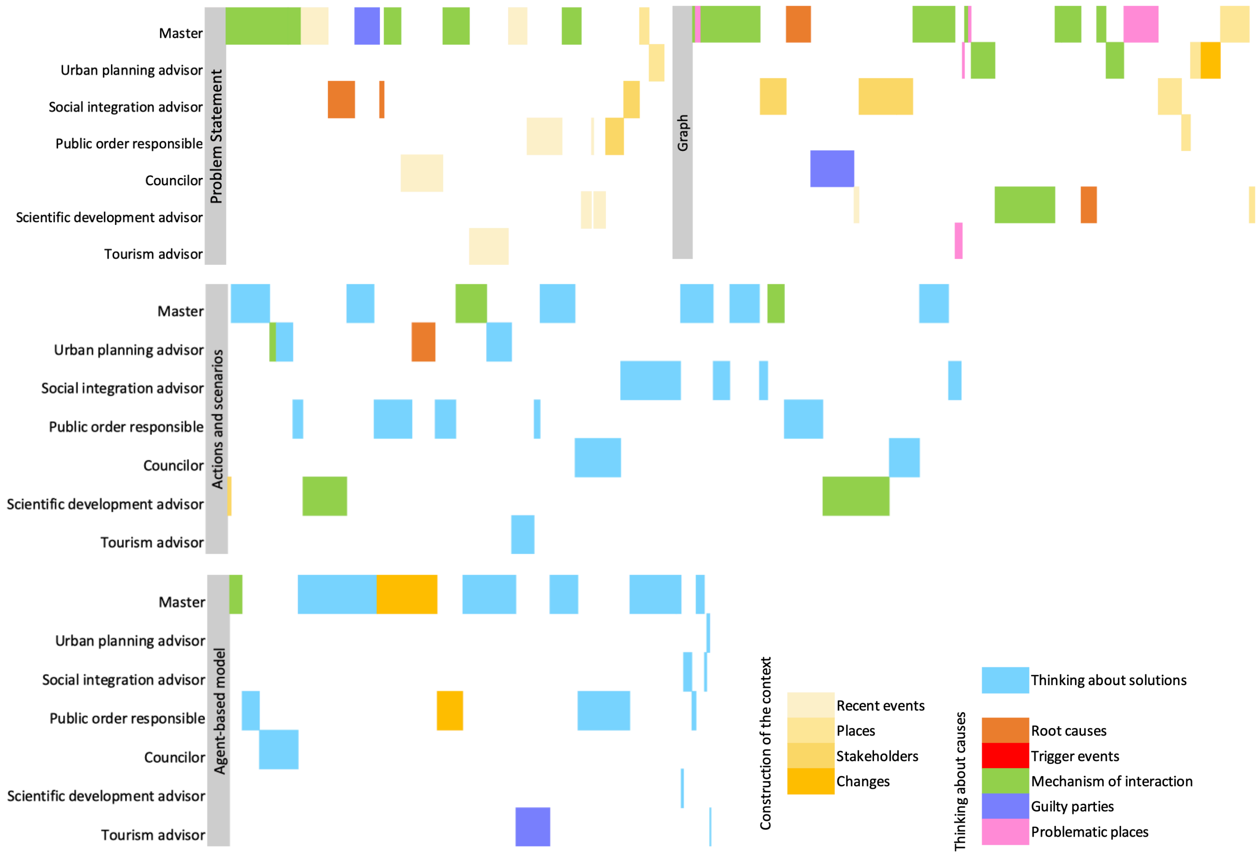


Figure 12. Coding of the group 2's discussion during the phases of the role-playing activity using the markers for i) construction of the context; ii) thinking about solutions; iii) thinking about causes. The length of the bars refers to the number of words coded with a given code in the specific piece of transcript.

Even with a preliminary look to the coded pieces of transcript, emerges that different phases of the role-playing activity have their own specificities in terms of reasonings activated by the students. We analyze each phase of the game separately, compare the two groups, and provide examples for our argumentation using students' words.

9.2.1. Phase 1: problem statement

The coding for the two groups for the parts that relate to the first phase of the activity is reported in Figure 13. As expected from the goals of the first phase, when the problem is introduced by the master, there is a predominance of markers for the construction of the context (shades of yellow) because the participants share the pieces of information they have about the problem.
The mayor presents the problem to the city council and asks what their opinion on that is:

> *Master (group 1): Let's go back to why I called you here. As I said, something happened to our city and the secret services sent me this email which I now copy to you in chat. As you can see a terrorist group has arrived in Xitta, it is forming, it is being seen ... for now it is made up of 20 people and it is not clear how this thing could have happened. You who are my trusted women what do you think?*

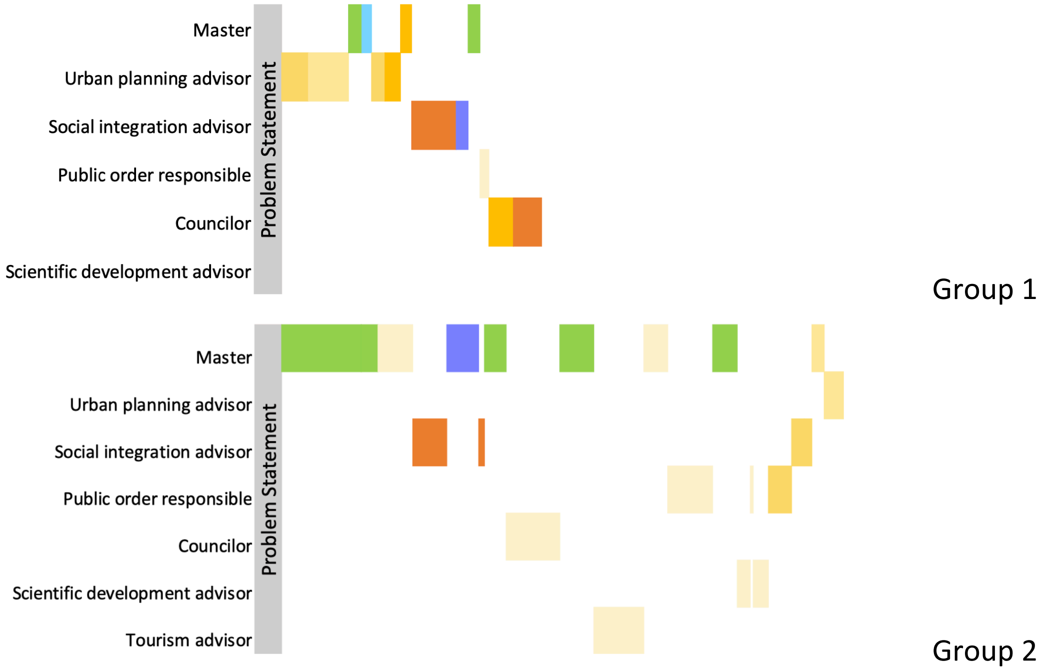


Figure 13. Coding of group 1 and group 2's discussion during the phase that follows the problem statement using the markers for i) construction of the context; ii) thinking about solutions; iii) thinking about causes. The length of the bars refers to the number of words coded with a given code in the specific piece of transcript.

The first reaction of the members of the city council is asking for more pieces of information in order to put the problem in a shared frame, literally to "construct the context" in which the problem of formation of the terrorist group is situated:

> *Urban planning advisor (group 1): First I would like to ask one thing. Regarding the formation of this group, of this aggregate of people, do we know if they have entered the city in recent months or is it a group of people who have lived in the city for years?* [construction of the context: stakeholders]
>
> *Master (group 1): I know as much as you do. This is the email that was sent to me and I don't know... I don't know...*
>
> *Urban planning advisor (group 1): Ok, as far as I'm concerned, I currently have maps of the city districts available and what I can tell you is that in a peripheral area of the city we notice an aggregate of people, or in any case a concentration of people... basically we have a peripheral area which is being very repopulated, probably due to migratory phenomena of various kinds.* [construction of the context: places]

The urban planning advisor takes the lead and asks to the master more details about the people that form this group (*do we know if they have entered the city in recent months or is it a group of people who have lived in the city for years?*) and then shares with the others the information she has received about specific places (*a peripheral area which is being very repopulated*) that could be of special interest with respect to the on-going issue.

Other elements for the construction of the context are given by the responsible for the public order and by the councilor with respect to recent events that have taken place and changes that have occurred:

Public order responsible (group 1): I meant that there has been a wave of vandalism in the city lately [construction of the context: recent events]

[…]

Councilor (group 1): In fact... I meant as I had already said a little earlier, I was told by the people who have always lived with me in the suburbs, that in the last period the conditions have really worsened. [Construction of the context: changes]

In the first phase of the role-play, there are not only elements for the construction of the context. Two students, playing the role of the social integration advisor and the councilor, make their first hypotheses on the root causes behind the observed phenomenon and the possible guilty parties[18]:

Social integration advisor (group 1): I had already reported that there were still some inconveniences... there are some inconveniences... we did a bit of a check, and in any case there are still some families who do not have equal opportunities and who have not yet integrated well, do not yet have a job that allows them to have a sufficiency, let's say, economic, and this certainly leads to finding alternatives, right? [thinking about causes: root causes] *And so let's see a little bit of basing our research on those people we had already identified as…* [thinking about causes: guilty parties]

[...]

Councilor (group 1): There have been many strikes by workers protesting the working conditions and also the recent layoffs, so there is a situation of strong discontent. And so if we're investigating the causes, well, this could also be... [thinking about causes: root causes]

We highlight that, if we follow the master's line, we see that he tries to guide the students to reflect on the ways in which the terrorist group has formed, hence on the mechanisms behind the phenomenon (green slots):

Master (group 1): So you have at hand, having the mapping, you know how you can move... how this group was formed [thinking about causes: mechanism], *how you could move towards a solution* [thinking about solutions]. *Well I'm glad you have...*

and, again:

Master (group 1): So you pretty much have an idea of how this could have happened...[thinking about causes: mechanism] *you saw movements, something?*

The same happens with group 2 where the mayor formulates similar mechanism-oriented questions:

[18] The excerpts are truncated and both students leave their sentences suspended but we can easily grasp the meanings of their discourse.

Master (group 2): But here we are talking about a terrorist group but I wonder why! What is the purpose? And how it formed, I'd be curious to know... a dynamic... I'm desperate. [thinking about causes: mechanism]

[...]

Master (group 2): In fact, I need you all because here the situation concerns culture, events, integration... someone will have to explain to me. Here I am addressing in particular the councilor for scientific development, a bit also the dynamics... the mechanism, if you have in mind... here we have to find an explanation for this thing... [thinking about causes: mechanism]

[...]

Master (group 2): Indeed, the message here speaks of "how could this happen", the secret services are also asking us about this. I can't find solutions so I'm appealing to your help, your reasoning, something... [thinking about causes: mechanism]

However, these stimuli to reason on the mechanism at the basis of the phenomenon and to answer "how" questions were not received by the other players. As we will comment in the next section, this will go on for most part of phase 2 too.

9.2.2. Phase 2: presentation of the graph

The coding for the two groups for the parts that relate to the second phase of the activity is reported in Figure 14.

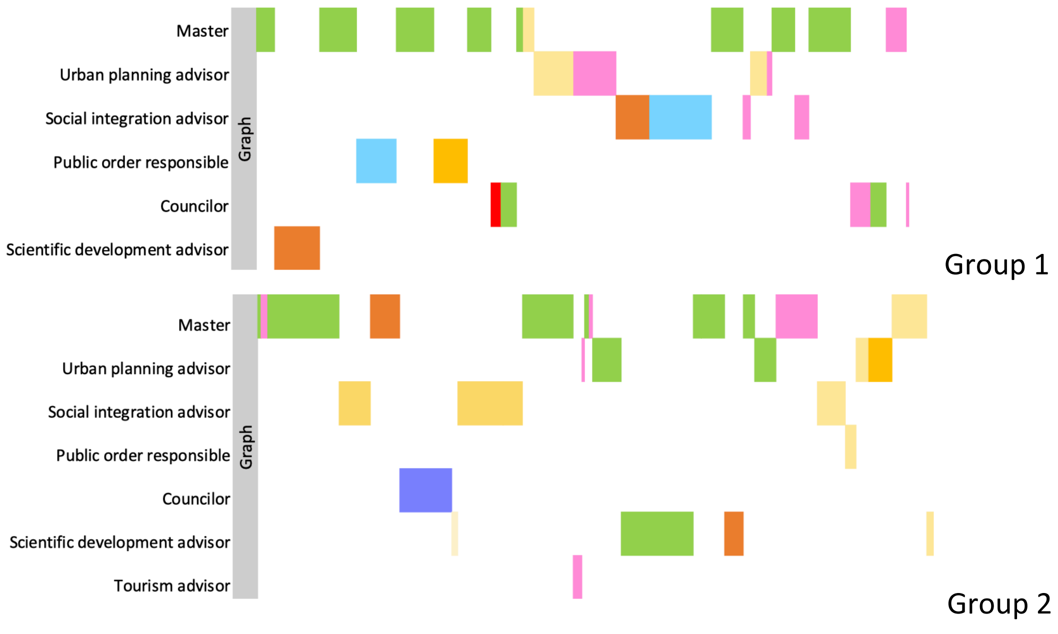


Figure 14. Coding of group 1 and group 2's discussion during the phase that follows the presentation of the graph using the markers for i) construction of the context; ii) thinking about solutions; iii) thinking about causes. The length of the bars refers to the number of words coded with a given code in the specific piece of transcript.

The second phase, characterized by the introduction of the linear graph for the increasing size of the terrorist network, aimed to make the participants elaborate hypothesis about the recruitment mechanism, excluding a virus-like process which would have led to exponential trends.

Because of this goal, in both groups the master's line is rich of markers for the mechanism of interaction (green). He encourages his city council in many ways, always trying to bring the discourse to focus on unveiling the mechanism of interaction that lies behind the linear function that seems to fit the data. However, it is very difficult for the other students to articulate an explanation on that. From figure 14, we notice that for group 1 we have only two occurrences of the mechanism code in the line of the councilor, while for group 2 we have both the scientific development and the urban planning advisor who reason on the mechanism.
In group 1, the scientific development advisor is the first to take the floor:

Scientific development advisor (group 1): So here we have what is called a trend... we have that in five months the percentage of people is just over 0.2% and we are 20 people. With this we therefore represent a trend, a forecast over the weeks of the percentage of the city's population that is in some way conditioned

Her first approach is to express the explicit information that the graph provides. Then we have an interesting piece of transcript in which, at the request of the mayor to explain "*what happened*", "*how the group came to be formed"*, "*how did it happen"* (green), the other students respond in different ways, searching for root causes of the phenomenon (orange), looking for solutions (blue) or adding other details related to the context (yellow):

Master (group 1): But, look, I only make percentages when it is period of sales... talk to me as I can understand. What is happening? I am very worried about the situation. What happened here? [thinking about causes: mechanism]

Scientific development advisor (group 1): Then here we have that from a certain point there was apparently an external input or even linked to what my colleagues were saying, some migration phenomenon or some discontent, which led to the formation of a criminal group which is expanding. [thinking about causes: root causes] *In my studies, among other things, I have developed this model of Axelrod which is applicable to the population to see even a little of this diffusion of ideas.*

*Master (group 1): I understand. But before moving on to a model, maybe even with the help of the others in my council we can see how this group came to be formed? From this trend, what do we understand about how it was formed? In the secret service message they told me it was important to understand how *emphasis* this growth has come.* [thinking about causes: mechanism]

[…]

Public order responsible (group 1): I have now seen that I have to reach mandatory hours for training courses for my service. I am attending refresher courses on the psychological aspects of conflict resolution within heterogeneous communities. So since lately, as my colleague said, many have arrived... that is... it has increased... in fact I'm studying a bit to solve the emergencies that may arise. [thinking about solutions]

Master (group 1): Well sure, with all due respect, haven't you seen something grow in this city? Otherwise, why didn't she stop her? You are a councilor for public order and here we have a growth. It is serious that you have not seen him. How is it possible? How did it happen? Have they gathered somewhere, in the squares? How did they communicate? We had 20 people expanding. [thinking about causes: mechanism]

Public order responsible (group 1): Yes, but it happened right now... that is... until now we have kept them under control, honestly. I realize the difficulties because, as the city planning councilor said, the surface of the *city has grown a lot and we have found ourselves with less strength to control the whole territory. This was the problem.* [Construction of the context: changes]

Despite the master's persistence, the mechanism form of reasoning remains inactivated in the other students. The only one who in this section start investigating the "story" behind that graph is the councilor:

Master (group 1): for now we have this graph... If you can maybe explain me a story of how this group was formed. I need to know a story. That is, how did they get in touch to expand, in your opinion? Who wants to speak? [thinking about causes: mechanism]

Councilor (group 1): In my opinion there must have been a triggering event that caused discontent among several people [thinking about causes: trigger event] *and from one person, two people will have come up with the idea of actively acting by doing something, and people around him will have started to gather.* [thinking about causes: mechanism]

Master (group 1): And how? That is, according to you, Miss Laura, how they gathered? [thinking about causes: mechanism]

The mechanism mentioned by the councilor is a gathering one, where there is an initial triggering event and, from one person, others are attracted and gather together. The master wants to ask more about the gathering mechanism, but other students take the floor adding context details (yellow), hypothesizing possible problematic places (pink), root causes (orange) and solutions (blue). The mayor interrupts these discourses because he wants to bring back the discussion to the level of mechanism, in order to make the students formulate a mechanistic explanation on the given graph:

Master (group 1): Excuse me if I interrupt you, but you are providing a solution to the problem. I want to know the cause. And more than the why, the formation mechanism. Where and how did they interact to expand their group? This is what I want to let social services know to help them. [thinking about causes: mechanism]

Social integration advisor (group 1): In my opinion they also meet in their places of worship, of religion. [thinking about causes: problematic places]

Master (group 1): Ok.

Urban planning advisor (group 1): I believe that if we think about the hypothesis of the agglomeration in the peripheral area I can still let you know that there are several buildings left abandoned, let's say, to companies that have closed [construction of the context: places]

Urban planning advisor (group 1): and therefore could easily be environments that... [thinking about causes: problematic places]

Master (group 1): So you say from person to person, if I'm not mistaken. This linear growth, if I understand what they say in the jargon, makes us think that these terrorists have seen themselves in places such as mosques, squares, churches, places... [thinking about causes: mechanism]

Social integration advisor (group 1): For me this is it, for me it is this. They do not occupy abandoned places. However, in this way they could attract the attention of the police. [thinking about causes: problematic places]

Master (group 1): The only growth I've seen in recent times is this virus, right? I do not know if you have heard this coronavirus going around the world... I have seen an exponential growth, it seems to me that they say, very different from this linear growth. So, I wanted to understand how it is that this growth is linear... so it doesn't work like a virus this expansion of these terrorists... it works in another way... [thinking about causes: mechanism]

Councilor (group 1): I could probably be wrong but it could be given by the fact that this growth, this spread, this expansion of the group is given because the expansion takes place in places of aggregation, such as social centers [thinking about causes: problematic places] *or in any case places where there can be exchange of opinions, ideas and therefore even more so also exchange of opinions regarding this terrorist movement* [thinking about causes: mechanism]

In the excerpt, we read how the master not only encourages the students to reflect on the mechanism, as he had already done before, but introduces specific elements to make the discussion more focused. In the beginning, the social integration and urban planning advisors do not reason on the mechanism, so the mayor recalls what the councilor said before about the gathering and says for the first time that the recruitment process happens *"from person to person"*. Later on, since the social integration advisor continues talking about possible problematic places in which the gathering could have been happening, he introduces another element for discussion which is the difference between the linear growth and another example of time evolution which is the exponential one, typical of the virus. In this way, he makes his request more explicit, so that the councilor can add to the previously detected "gathering mechanism" the idea that it happens on the basis of an "exchange of opinions". It remains still unexplained the difference between the linear and exponential growth and between the processes that can led to the two.

In this excerpt we have noticed a strategy, facilitated by the master, of "narrowing down". He starts from the previous idea of "gathering of people" and focuses on the "person to person" spread. In this way, he moves from the aggregate level of the group of *people*, as the councilor had hypothesized, to the local level of the single *persons*. In this way, he tries to set the basis for the following explanation in the local level of agents' interactions, instead than on the aggregate level of groups of people that grow or diminish. Then, using the counter-analogy of the exponential growth of the virus spread, he wants to guide the students to a more detailed and mechanistic description of the person-to-person interaction, in some sense to better characterize the way in which the terrorist group is formed.

A similar dynamic is observed in group 2:

*Master (group 2): The thing that I would like to understand a little, to then perhaps take some measures, possibly... in your opinion, how does recruitment take place? That is the recruiting mechanism. This is what we want to understand. Because here they ask me for solutions. My ethics require that I, who we *emphasis* - because we have to work together, we can't, say, then dump the barrel and point and blame each other - we have to find a strategy! So understand the mechanism by which this group was formed* [thinking about causes: mechanism]

Tourism advisor (group 2): we can assume that the recruitment takes place perhaps during the festivals or during certain events... [thinking about causes: problematic places]

Urban planning advisor (group 2): So in aggregation points! [thinking about causes: problematic places]

Master (group 2): So you say physical contact recruitment. [thinking about causes: mechanism] *These are found in some places...* [thinking about causes: problematic places]

*Urban planning advisor (group 2): In direct contact... it is as if from the linear trend, we have a linear trend that starts right from the origin, so I would say that in the case, doing - now, okay, sorry *laughs* - extrapolating the coefficient we could also understand the number of people being affected at a time.* [thinking about causes: mechanism]

Scientific development advisor (group 2): Honestly it seems a bit more complex to me, because ... okay, we can, as the councilor for social integration suggested, exclude that it is something that came from outside. However, maybe it is something born that then spread. The most, as the mayor said, is to understand how it has spread and I don't think it can only be a spread within the narrow range. Ok, maybe people have also met on the web or in any case other types of adherences to terrorist sects are not to be excluded because in my opinion it can happen on the internet... so this thing cannot be excluded either. This is why I say that the system is more complex than it... [thinking about causes: mechanism]

[...]

Master (group 2): and why is it slow? Better!! But I really want to understand the mechanism because we have to intervene with measures! [thinking about causes: mechanism]

Urban planning advisor (group 2): must be a selected recruitment probably! That is, probably in order not to be discovered they obviously do not speak to the general public but select and therefore this selection takes time and recruitment takes place more slowly. [thinking about causes: mechanism]

Even in the case of the group 2, the first that explicitly mentions the type of mechanism is the mayor itself, talking about a "physical contact recruitment". Then, the urban planning and the scientific development advisor make some reasonings to connect the graph they are observing to the possible recruitment dynamics. The urban planning advisor searches in the graph information to describe the rate of recruitment and, noticing that it is constant and low, the scientific development advisor hypothesizes a "narrow range spread" and a "selected recruitment dynamics". Differently than in group 1, here the emphasis is not on the gathering or exchanges of opinions, but on the rate at which this happens.

9.2.3. Phase 3: actions and scenarios

The coding for the two groups related to the third phase of the activity is reported in Figure 15.

Figure 15. Coding of group 1 and group 2's discussion during the phase that follows the presentation of the possible actions and scenarios using the markers for i) construction of the context; ii) thinking about solutions; iii) thinking about causes. The length of the bars refers to the number of words coded with a given code in the specific piece of transcript.

When three different scenarios of intervention are introduced in the third phase, the group mainly reasons about possible solutions to the problem, as expected from the goals of this phase. We can notice from Figure 15 that blue is the most frequent color in this phase for both groups. However, there are some exceptions.

In group 1, the first to comment the three possible strategies of intervention is the public order responsible who considers the line of action that foresees the increasing of the community police. In particular, she motivates her idea of solution associating the causes of the phenomenon to the low number of police officers in the city:

> *Public order responsible (group 1): That's what I was saying... we are few!* [thinking about causes: root causes]

The social integration advisor reacts. In her view, the best intervention is that with social workers. However, it is remarkable the way in which she argues about it:

> *Social integration advisor (group 1): I do not agree on increasing the number of policemen because the phenomenon must not be physically fought, terrorist-policeman, but must be treated, the problem, the source, must be cured.* [thinking about causes: root causes]*. So, by increasing the number of social workers the problem is solved, it is not fought only momentarily. Not only are they prevented from carrying out terrorist attacks but rather trying to resolve the situation, right?* [thinking about solutions]

As the public order responsible, also the social integration advisor considers root causes to decide the strategy to adopt. The difference is that the social integration advisor distinguishes between the root causes and the phenomenon which can be observed at the surface, and this leads to a second distinction between solutions that fight a problem only momentarily and others that cure a problem. The councilor, who supports the third intervention, related to work, argues for it considering another level of causes, which is that of specific trigger events:

> *Councilor (group 1): Yes, I agree with Rita and in addition I believe that it is also important to encourage employers to hire individuals at risk...* [thinking about solutions] *because if it is true that there are so many work problems and there have been so many layoffs* [thinking about causes: trigger events]*, it is the case to act on this aspect.* [thinking about solutions]

This section of the game continues alternating speeches supporting the different strategies of solution (blue), sometimes associating them to the causes of the on-going problem, represented by the guilty parties (violet).

Approaching to the end of this phase, the scientific development advisor takes the floor and tries to analyze the three strategies of intervention in terms of the elements of the model they impact:

> *Scientific development advisor (group 1): With the collaboration of my colleagues, if we can still obtain data relating to the current situation, in order to have something to start from, thanks to my great power I could still make predictions, thanks to my model, of what it would be the evolution of the phenomenon, putting, for example, various variables. Obviously, increasing the number of social workers involving individuals at risk can have on the one hand some repercussions that may perhaps be negative on the current situation, because it favors exchanges. While certainly increasing the controls reduces the*

interactions, and therefore in that sense they are parameters that you can see how they could influence the progress of this wave of underworld. [thinking about causes: mechanism]

[…]

Scientific development advisor (group 1): Look, Mr. Mayor. I, from the point of view of what may be data, I can say that, given that we have this linear growth and we want to avoid, as for example in the case of the coronavirus, what is an exponential trend, certainly decreasing the interactions decreases the possibility of exchanges. This obviously has negative sides, because it goes well to affect spheres of competence not mine, as regards funds or other... But for example, among all the choices, maybe a job could possibly expose those who are already part of the association with a more educational environment, if we want to put it, and in some way maybe remove them from the underworld idea and decrease the general discontent. [thinking about causes: mechanism]

Master (group 1): Uhm. And instead the police intervention, what was it called? Can you analyze it for a moment? What would it lead to? How do you see it?

[…]

Scientific development advisor (group 1): There is my real nature that pushes me not to suggest an increase in the police force but more the apparatus of employment. Social workers is the only thing that I would exclude because in reality centers are created that could act as a point of further diffusion of this thing. [thinking about causes: mechanism]

Master (group 1): Do you deduce this from your very difficult books of calculations or do you see it from...?

*Scientific development advisor (group 1): Yes, from those where there are only numbers, not even a letter * laughs **

Master (group 1): How do things work there? How would the numbers do? Excuse me for the somewhat trivial question maybe...

Scientific development advisor (group 1): So, look, the numbers... So in a case where you increase the center, as somehow in my model increasing what is the range of action of a single individual, consequently you increase the risk of growth with an even higher rate. While if we go for example to suppress, as the police did...

Master (group 1): You are talking about a model you mentioned earlier... can you briefly summarize it for us?

Scientific development advisor (group 1): Practically in my model, every single agent has the possibility of transferring certain ideas to the other individuals around it. [thinking about causes: mechanism]

Master (group 1): So we're talking about a person-to-person exchange as we assumed earlier, right? [thinking about causes: mechanism]

Scientific development advisor (group 1): Exactly. And the fact is that the closeness between these people favors the exchange of these ideas and the tools they have. For example, social centers are a very powerful tool because they allow a single person to reach many, while isolating them would make them more harmless. [thinking about causes: mechanism]

In this excerpt, the scientific development advisor considers the impact of the different possible actions based on the current situation. To do that, she reasons explicitly on a model (*"thanks to my model, of what it would be the evolution of the phenomenon, putting, for example, various variables"*), in particular the Axelrod's one that she had explored during the previous activity. Of all the elements of this model, she mainly reasons on two of them. The first is the mechanism of "exchange" that rules the agents' interactions (*"Obviously, increasing the number of social workers involving individuals at risk […] favors exchanges. While certainly increasing the controls reduces the interactions"; "every single agent has the possibility of transferring certain ideas to the other individuals around it"; "the closeness between these people favors the exchange of these ideas").*

The second, connected to the first, is the idea of diffusion ("*Social workers is the only thing that I would exclude because centers […] could act as a point of further* *diffusion* *of this thing*").
Even though the scientific development advisor extensively talks about the mechanism of the model with which can be interpreted the problem, the other students do not share with her the same level of discussion, continuing reasoning on the possible solutions without entering the mechanism dimension.
In group 2 happens mainly the same, where the scientific development advisor remains the only one who analyzes the different interventions from the point of view of the underlying mechanism. However, even if with similar argumentations, he supports a different type of intervention, that with policemen:

> *Scientific development advisor (group 2): Also in my opinion. I support this* [the increase of policemen], *because in these cases it is very useful to decrease the... to circumscribe the problem, therefore the area and the people who could be affected* [thinking about causes: mechanism]. *And I repeat what I said earlier, that interactions can be very dangerous. At the same time, however, I agree with the councilor for social integration because it is right to find something in common with these people. You cannot clearly interact without anything in common... even the model I am studying is at the basis of this too... and therefore, let's say, it is right maybe later on, maybe to look after that too, therefore integration and at work, so that these people have... because objectively what do they have in common with our citizens? very little! Therefore...* [thinking about causes: mechanism]

9.2.4. Phase 4: introduction of an agent-based model

The coding for the two groups of the fourth phase of the activity is reported in Figure 16.

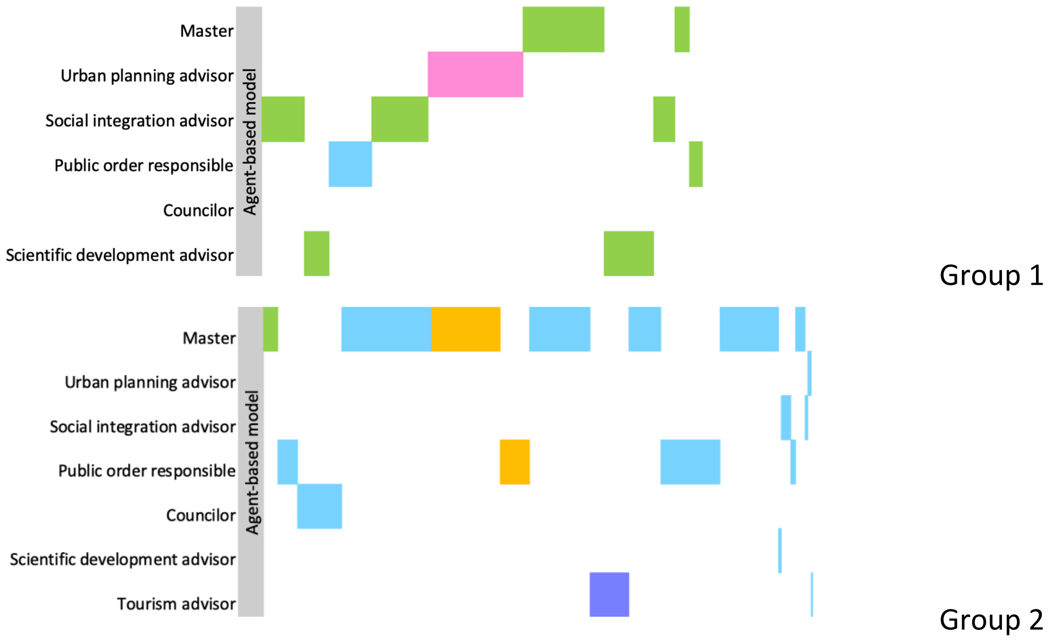


Figure 16. Coding of group 1 and group 2's discussion during the phase that follows the introduction of an agent-based model using the markers for i) construction of the context; ii) thinking about solutions; iii) thinking about causes. The length of the bars refers to the number of words coded with a given code in the specific piece of transcript.

In the last phase of the game is introduced the agent-based model at the basis of the PROTON simulation. In this case, as we can notice in Figure 16, the two groups differ a lot. The first big difference is the fact that in group 2, the main actor remains the mayor, while in group 1 the discussion is mainly articulated by the rest of the group. We will articulate our discussion on the role of the reflection about the mechanistic dimension by analyzing separately the two groups.

Group 1's discussion is characterized by the presence of reasoning in terms of mechanism of interaction (green), following the exchanges at the end of the third phase. The difference between the third and the fourth phase is that in the last one there are three students and the master that take part to the discussion on the mechanism level, while before it was a prerogative of the scientific development advisor.

> *Social integration advisor: I wanted to make an intervention regarding the use of a program, a simulation. As I am a councilor for social integration, we know very well that agents are more inclined to interact with those who are more culturally similar. So there is an integration between two agents... the more similar they are, the more they tend to aggregate culturally.* [thinking about causes: mechanism]
>
> *[…]*
>
> *Social integration advisor: The more similar they are, the more people are inclined to interact with those culturally more similar!* [thinking about causes: mechanism]
>
> *Master: You, Elisa, what do you think?*
>
> *Scientific development advisor: So I, by supporting an integration, eventually forms a group of people who have common basic values that are less inclined to deviate from what is the civil life shared by most.* [thinking about causes: mechanism]

The social integration advisor recognizes the idea of interaction between agents where this interaction is mediated by the similarity of the agents themselves. When the public order responsible insists to go for the intervention with more policemen, she reaffirms the motivations to avoid this kind of action on the basis of the underlying mechanisms:

> *Public order responsible: If you want to solve it immediately, Mr. Mayor, give me more men and I'll take care of it.* [thinking about solutions]
>
> *Social integration advisor: No, no, I reiterate my concept. Science, simulations, mathematics show us that by increasing the people who interact, who have cultural characteristics as similar as possible, there is a greater chance that there is integration, that there is a single culture and therefore there is greater integration between people.* [thinking about causes: mechanism] *So I say that if there are few funds, those must be invested in the social sector, in the sector in which there is integration, equal opportunities, so that there are as many similar aspects between people.* [thinking about solutions]

We notice the difference between the argumentations of the two characters. On one side, with the public order responsible, we have only the statement of a solution, on the other, with the social integration advisor, the proposal of a solution is motivated with the recognition of the mechanism on which the specific solution would act, in this case the increasing of cultural similarity.

Approaching to the end of the activity, also the public order responsible joins the social integration and the scientific development advisor in considering the mechanistic dimension. On the opposite, beside the councilor, another who stays on the side of this discussion is the urban planning advisor.

At the beginning of the previous phase, she was the one who had been corrupted from the terrorist network and she was asked to play against the most common decision of the rest of the city council. Even if we cannot confirm this hypothesis, this could be one of the reasons for her to avoid touching the mechanistic dimensions.

As we mentioned at the beginning of the paragraph, group 2 shows a very different codes' distribution for what concerns this last phase of the game. What we did not report in the figures are the uncoded excerpts that in this phase and for this specific group are a lot. Indeed, the group spends most of time to comment the aspects that the model takes into account and what it does not consider, and to reason on the opportunity to actually use a model and a simulation to take a decision on this complex problem. This kind of discussion is triggered by the master himself:

Master (group 2): So I ask you: can we trust this thing? would you trust? just like that a leap in the dark... because I have never experienced these things... I am also a stranger...

Urban planning advisor (group 2): it seems to me too simplistic from a certain point of view. I'm afraid that it can help us up to a certain point by taking a range of people so large that it is not useful... we would take too long to control maybe each of them, each of these people...

Master (group 2): do you make it a question of population size? In the big it doesn't work... did I get it wrong?

Urban planning advisor (group 2): In my opinion maybe it could work but it could take even longer than expected. However this is a simulation in which the time scale is six months... we have said that in five months we have the elections and we would give a solution too late!

Public order responsible (group 2): in fact I too was wondering about the timing... I think it's such a delicate situation that maybe... I don't know...

Master (group 2): but a note that I seem to have read... the time scale of the six-month model I am afraid that it refers to the study done, in the six months... from here it seems that they have tested the model in six months, not the six months to come! I think so. I do not know if the councilor for scientific development can elucidate this aspect.

The discussion is not oriented at explaining or solving the on-going problem but rather at analyzing the potential of a model to address it. For the councilor, the simulation itself becomes a part of the possible solutions to the problem:

Councilor (group 2): and then based on this, I do not say making decisions based on this alone, but we could make it become a tool that then allows us to choose based on that, which path to take first. Always to keep in mind that several paths must be taken, but perhaps choose which path must be the most instantaneous one and the one that is more long-term, also depending on what the simulation tells us. [thinking about solutions]

One thing that we did not observe in group 1 is the presence of codes for the construction of the context (yellow) that are introduced in the discussion by the master and then followed up by the public order responsible:

Master (group 2): through a web control the recruitment could take place... understanding a little what is the perception of integration in our town could happen in this way. Responsible for public order, you told me about some vandalism or tensions in the Palazzoni area, these things here... we have also data regarding this. It is true that our town is a quiet town, but there have been some events lately - at the *beginning you also gave me a report - of tension. I don't know if you have any data also with respect to the tensions between different groups that exist in our town... if you can update us on anything, if you have had...* [construction of the context: changes]

Public order responsible (group 2): Well, we have no data in this regard, because in short we were informed of these vandalism that was taking place in that area and we intervened and found some responsible and we closed the matter. But surely we can get some information. [construction of the context: changes]

Master (group 2): ok. And so let's say that by reasoning about these aspects of perception... we could somehow get the data... it could be a bit slow path...

Scientific development advisor (group 2): in my opinion too slow and too multifaceted. All this information comes from a questionnaire or from something done about many people...

We underline that in this phase of the game the elements for the construction of the context have a different role than in the beginning of the game. Indeed, here they are suggested by the master as elements to be investigated in order to give the model some inputs on which calculating the evolution of the system.

The discussion goes on with the discussion of the possible solutions (in the long or short term) and the identification of possible guilty parties to whom the interventions should be addressed:

*Master (group 2): maybe we could do this: we could commission the secret service agency to do these studies - maybe they are much faster than us, much faster - so we can reason from the assumption that we have the data available. So the model can be applied effectively, let's put it this way. So, at this point I ask you with this model is it possible to obtain some more solutions, some more ways, have more data, reason *emphasis* on possible alternative solutions, perhaps multiple compared to the one we had taken before? Or change strategy or even add others if necessary.* [thinking about solutions]

Tourism advisor (group 2): Well, through the simulation we can still have an idea of which social groups, let's say, based on sex, age and religion... which groups are closest to radicalization and also based on what motivation... maybe sex, maybe young people are more easily recruitable... so on... we can have an idea on which subjects to work more... or groups, rather than subjects. [thinking about causes: guilty parties]

Master (group 2): ok

Scientific development advisor (group 2): yes, narrow down the problem, as we said at the beginning

Master (group 2): so if we were to find a solution by possibly using simulation or rethinking what we had said previously, how would you articulate a possible plan to attack this terrorist expansion? To this formation of terrorist groups in our community... what solution would you adopt? Even multiple in this case... public order? Any ideas? [thinking about solutions]

Public order responsible (group 2): I was always thinking, therefore, about two actions. One short-term and one longer-term. Thanks to the intervention of the police, we can keep the areas concerned more under control and maybe move in the direction of also obtaining data, information that may be useful for this model. This may be a general idea, however, since this terror situation has occurred once it doesn't necessarily mean it won't happen [again] and the next time we may find ourselves benefiting from this collection of information, let's say... this in the short term [thinking about solutions]

As we can see in Figure 4, for group 2, the mechanistic dimension remains in this phase of the game inactivated. We have only the master who, in the beginning, recalls the type of interaction “by contact” that the group has mentioned in the previous phase:

Master (group 2): So as you said before, these terrorists recruit people by contact, which could be physical contact but also via the web... [thinking about causes: mechanism]

We have seen that in the case of group 1 it was the reflection on the analogies with the Axelrod's model to trigger a reflection on the mechanisms behind the phenomenon. Also in group 2 the students mention this model but, coherently with the rest of the discussion in this phase of the game, they remain at a level of the data on which the model is based and the parameters considered, without entering the dynamics of interaction that constitute its foundations.

Master (group 2): So you suggest an intervention to increase the police, increase the controls of this type in the short term, and then have more data to be able to apply the simulation and get more information from the simulation later, later... even if, I repeat, in my opinion in the short term the secret services may already have data, results on this aspect, on these things here. Nothing has been provided to me yet, but if they have proposed this model to me it also comes to mind that there is already a trend... that they have already understood something more, in short... this is the model that we was subjected, with these assumptions and we were asked...

Scientific development advisor (group 2): yes, if they have put these parameters it means that they have studied the situation and found the best parameters to represent this model.

Master (group 2): if we wanted to close?

Urban planning advisor (group 2): I don't want them to have old data, though? Data that over time could become obsolete ... so if we could somehow recover these data ... but this too would lead to slowdowns.

Master (group 2): Excuse me, councilor for scientific development. But what data are there in the Axelrod model?

Scientific development advisor (group 2): what data, that is, what parameters?

Master (group 2): ah so there is no data? I want to understand this thing here of the data?

Scientific development advisor (group 2): no, there are parameters that one puts in, which are cultural characteristics, traits and precisely the quantity of population, which obviously can be decided, you can see based on how much data we will have, of course, and the radius...

Master (group 2): so I understand that a data collection problem where is it? that first came out... I don't understand this, because you told me that there is a data problem and therefore the simulation maybe doesn't work ... but scientific development is telling me now that we are talking about parameters and how... no data are entered there, no external data! These parameters are entered, then this device is sent, as it were, into operation...

Scientific development advisor (group 2): yes yes yes exact... so... it is also independent... the data that is collected, I would like to say, can be related to a part of the population, to... that is, a lot can be done simulations, or many hypotheses, by changing these parameters.

For this group, presenting the basics of an agent-based model and recalling the Axelrod one does not have the effect of motivating the decision of intervention basing on mechanistic reasonings. On the opposite, the students limit themselves to analyze the inputs of these models ("*if they have put these parameters it means that they have studied the situation and found the best parameters to represent this model*") and to wonder if in the current situation could be collected enough data and of sufficient quality to "feed" the simulation ("*I don't want them to have old data*"). Even the explicit description of the Axelrod's model and simulation is limited to touch these aspects, without entering the mechanism on which it is constructed ("*there are parameters that one puts in, which are cultural* *characteristics, traits and precisely the quantity of population, which obviously can be decided, you can see based on how much data we will have, of course, and the radius*").

10. Discussion

We began our study, in Section 2, stretching the need for the development of decision-making skills that every citizen – from the local communities of common citizens to the most influential leaders and spokespersons – should develop. From the work by Al-Dabbagh (2020) we cited ten competences that are important for any societally relevant decision-making process, especially when interventions must be decided in a short period of time to face some kind of crisis. These skills were: 1) Collecting information about the issue under study; 2) Developing alternatives and possible solutions; 3) Comparing and choosing among the available alternatives to face the issue; 4) Predicting the consequences of possible solutions and alternatives; 5) Analysis, correlation, and conclusion; 6) Evaluating the results of solutions taken to face the issue; 7) Diagnosing the current situation; 8) Communicating with the parties; 9) Solving problems using traditional and creative methods; 10) Critical thinking. In the light of the results of the study we can say that an activity as that we have proposed is well-positioned to make the students experience first-hand the competences that are needed by policy makers. For example, in the first phase of the role play, the students understood that, before making hypothesis on the causes of the terrorist emergency that is taking place and thinking about solutions, they had to collect information on the issue (1). By the same design of the activity, collecting information about the problem required exchanging information between different stakeholders (8), recognizing that each of them had their own perspective, expertise, and knowledge to share on the issue under study. Moreover, the roles of the participants had been deliberately written to allow the students, when putting in common their pieces of information, to construct a more complete puzzle of the current situation (7). In the second phase of the game, the graph was presented to the students as another element that can be used to clarify the present state of the system (7), as the result of a linear trend of the number of recruited people. Even if the data analysis showed a relative inefficacy of the graph to trigger mechanistic reasonings with respect to the expectations, this phase of the activity had been designed to trigger analytical thinking in the students (5). In this case, the term "analytical" has for us a very precise meaning: to recognize that a series of data – that can be mathematical represented with a linear function – can be interpreted in terms of the phenomena (in this case, types of interactions between individuals and recruiters) that lie at its basis and, conversely, that different phenomena give place to different data and interpolating functions. When we move to the third phase, with the request to the students of evaluating three types of intervention to deal with the problem, there are many messages that the activity wants to deliver. On one side, the fact that a problem can envision a variety of possible solutions and that in real decision-making contexts there is a finite set of alternatives – suggested by experts or dictated by actual reasons of feasibility – that can be discussed (2). These alternatives need to be evaluated and compared in terms of the scenarios they would lead to, including the direct and indirect consequences of the interventions taking place (3, 4). In the specific case of our activity, the comparison could be made even more explicit in the fourth and last phase of the game, when the features of the agent-based model and simulation were presented. Here, the students were given the possibility to analyze the three interventions introduced before in the light of the “leverage points” of the model on which they act (e.g. the intervention on employment influences the routine and diminishes the time spent for radicalization; that on police officers impact the agents’ opinion on trust toward the institutions; that on social workers has effects on the other sensitive opinions). When the role-play activity ended, to the students were presented the actual results of the simulation through the PROTON-Wizard application: doing that, we show how the results of solutions can be evaluated also on the light of computer-simulated scenarios (6).

11.Conclusions

The analysis show that different students’ forms of reasoning were observed through the phases of the role-play. Elements of scientific information such as graph – which were a priori relevant for triggering the mechanistic dimension as an essential basis for the explanation of the complex simulated phenomenon - were not so effective. On the other side, having explored the simulation of a basic model of opinion dynamics served as a good starting point to reflect on the mechanism of phenomena and to compare intervention scenarios before making informed decisions. It was the peculiar distribution of the mechanism form of reasoning along the group’s discussion that allowed us to raise this point. Indeed, in the first two phases of the activity, markers for the mechanism can be recognized almost exclusively in the master’s interventions. Only in the end of the third phase of the activity and during the last one, the mechanism appears in students’ discourses. Here, the idea of one-to-one interaction with a recruiter is triggered by the introduction of a specific example related to the Axelrod’s model. As, in that model, local interactions among agents lead to global patterns of polarization, the same happens in terrorism simulation where the interactions among agents lead to the spread of radical opinions. The mechanism experienced through the Axelrod’s simulation served in this case as a productive analogy, becoming a way to inspect the phenomenon and discuss pros and cons of different scenarios of interventions.
In conclusion, even if the individual phases of the role-play did not always reach the prospected goals, the activity as a whole allowed to unveil the forms of reasoning activated when a simulation is presented as a citizenship tool.
From this study, we argue that the potential of simulations lies also in their multifaceted character that embed a diversity of knowledge forms; each of them has its own specificities and can trigger different reasonings on the same simulated problem. Simulations, if properly addressed in education, can lead to the development of decision-making skills as competences that allow to navigate the diversity of forms of scientific knowledge and to extract relevant meaning from them.

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Chapter 7 -
Computational simulations to develop future-scaffolding skills[19]

1. Introduction

In this final chapter we present the design, implementation, and analysis of a module on simulations of complex systems targeted to upper secondary school students. This module was situated in the context of the Italian national program that aims at orienting high school students to the choice of a scientific university course (*PLS – Progetto Lauree Scientifiche*, Scientific Degrees Project). The Department of Physics and Astronomy of the University of Bologna offers every year a variety of opportunities for the students to encounter the frontiers of the research in Physics and to enrich their ideas about what the jobs of physicists can be. For the academic year 2020-2021, the educational offer of the department was enriched with the introduction of this innovative course that we have personally curated in all its phases. In this chapter we will describe in detail the module and we will show how its articulation aimed at making students reflect on the wide potential of computational simulations to provide knowledge on societal issues, to think about interdisciplinarity and to enrich their imagination and ways of thinking about the future. Particular emphasis will be dedicated to underline how the module was constructed in the light of the most advanced literature findings on agent-based simulations which are the main object of instruction. During the first implementation of the module with 35 participants in January and February 2021, several data were collected through questionnaires, focus groups, collective discussions, and individual interviews. The richness and multidimensionality of data led us to identify different *foci* of analysis.

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[19] The contents of this chapter have been partially presented in an extended abstract for the ESERA 2021 Conference (Barelli & Levrini, 2021a) and in the oral presentation at the SIF 2021 Congress (Barelli & Levrini, 2021b). The former has been extended for publication in the proceedings (Barelli & Levrini, submitted a), while the latter has been selected as one of the best communications of the conference and we have been invited to submit a paper on an international journal (Barelli & Levrini, submitted b). The analysis on the potential of the module to develop future-scaffolding skills has been submitted and at the date of dissertation’s delivery is under review (Barelli & Levrini, submitted c). Another extended abstract has been selected for a special issue of future-oriented science education and the extended version will be submitted soon.

The analysis presented in this chapter aims at investigating the module's potential in fostering the development and the put into action of the so-called future-scaffolding skills (Levrini, Tasquier, Branchetti & Barelli, 2019; Levrini et al., 2021) as abilities to navigate the uncertainty of the future through a rational scaffolding. We analyzed two different sets of data collected during the course: the seven group's presentations that came at the end of the future-oriented activity, and eight individual interviews. The presentations were used to identify structural and dynamical skills put into play by the students in the analysis of a complex topic through computational agent-based simulations. The individual interviews were used instead to check if the students were able to express the development of these competences. Two emblematic case studies have been identified as crucial to interpret the significant gap between the competences "in action", displayed and put into play in the presentations and those that the students could recognize and express with their own words during the interviews; the analysis of these case studies will be addressed in further works. To conclude the study, in the light of the empirical results of the part study, we present an operationalization of the future-scaffolding skills as competences that can be grounded in the conceptual and epistemological aspects embedded in agent-based simulations and in the design principles of the future-oriented activity.
However, this is not the only type of analysis carried out on the data collected during the module's implementation. These works are reported and articulated in three part studies that are presented at the end of this chapter:

Part study 1 – Agent-based simulations to think about societal issues
Part study 2 – Simulations to construct scenarios of equilibrium for complex societal issues
Part study 3 – Students' desires about the school of the future

2. Design principles at the basis of the module

As we advanced in the introduction, the module was constructed around three main issues that simulations of complex systems can help addressing: i) interdisciplinarity, ii) the relationship between physics and societal topics and iii) future.

2.1. Simulations as interdisciplinary objects

Computational simulations touch the interdisciplinary topic in many different ways. That more obvious regards the *variety of application fields* of the simulations as a tool of research. In the 50s, simulations became a standard technique in the domain of Physics (Galison, 1996) but nowadays their use is so much widespread in all disciplines, from natural to social sciences, that it would be difficult to find a single field of inquiry in which an attempt of investigation through this method has not been made.
Another interdisciplinary perspective on simulations regards the *collaboration between experts in different fields*: for example, to realize a reliable simulation on organized crime as that presented in Chapter 6, criminologists, psychologists, neuroscientists, experts in agent- or equation- based modelling, computer scientists, engineers and designers have to work together. If the simulation

has been designed to be use from non-expert public, also professional in science communication should be involved in the process of simulation construction (Thagard, 2005).

We can recognize a third meaning of interdisciplinarity if we put aside the source domain and focus more on the concrete simulation artifact. Indeed, in the computational model which lies at the basis of a simulation there is a *multiplicity of disciplinary concepts involved*. As we have shown in Chapter 5 with the SIR model, the same ways of embedding stochasticity in a simulation can reflect different mathematical perspectives on the idea of probability which, as a consequence, reflect themselves in the computational implementation.

The interdisciplinarity that characterizes computational simulations at many levels can led us to think at them as "boundary objects" according to the definition of Akkerman and Bakker (2011), i.e. artifacts that bridge different domains and trigger interdisciplinary collaboration and understanding. In the module, the reflection on interdisciplinarity was implemented in different ways. For example, we organized a round table with Ph.D. students and early career researchers who, within the Department of Physics and Astronomy, work with simulations in different fields (epidemiology, nuclear physics, accelerator physics, climatology, astronomy); in this way the students could see the variety of research that can be done with and on simulations. In the following parts of the module, the students were guided to see how simulations are powerful tools not only in physics and in the natural sciences but also in social ones, to describe for example processes that involve changes of opinions.

2.2. Simulations as bridging objects between physics and society

This second design principle is strictly related to the interdisciplinary issue raised above but here we want to stress the reason why addressing societal topics starting from the physical perspective, in a course, like the PLS laboratory, organized by a university department of physics. The science of complex systems has challenged the idea of compartmentalized disciplines unveiling an image of physics beyond the "traditional" meaning of physics (Holovatch, Kenna & Thurner, 2017; Ball, 2016) as essentialist, deterministic, reductionist and in search of universal natural laws (Mayr, 2004). Moreover, "in this era of interdisciplinary science, of biological physics, network science and econophysics, defining physics as the science of the properties of matter and energy is increasingly outdated and inaccurate" (Sinatra, Deville, Szell, Wang & Barabási, 2015, p. 791). In front of these challenges, the characterization of physics as a field has recently passed from an epistemological question ("what is physics?") to a more operational answer: "physics is what physicists do"[20]. The work by Sinatra and colleagues (2015) applying tools of network science to the analysis of specialized journal has shown that nowadays there is a widespread distribution of physics literature which is not published in physics journal even if the subject matter and referencing patterns are indistinguishable from the core of physics literature.

In the module, we addressed the transition from physics to the societal realm with the voter model, passing through the analogy with the Ising system. Indeed, as we can model a ferromagnet with 1

[20] Quotation by Sam Edwards in (Donald, 2014).

or -1 spins occupying a grid where they begin to align following the spin value of their neighbors, the same dynamics can be observed and used to model social systems to describe the reach of social consensus. On place of 1/-1 spins there are yes/no opinions hold by voters and on place of ferromagnetic properties of the material what is observed is the reach of consensus or not on a certain decision. This example – but many others could be identified – makes explicit the connection between physics and social sciences. Not only the inquiry methods of physics are used to analyze, investigate and experiment with social phenomena (Ball, 2016) but the inner *dynamics* of physical systems become *models* to describe behaviors in other fields.

2.3. Simulations as future-oriented objects

As we have argued in Chapter 3, simulations can have different purposes. Grüne-Yanoff and Weirich (2010) list four possible uses: proof, prediction, explanation, and policy formulation. The issue of policy formulation and prediction are related; with the climate change emergency, and even more in the last months, for the COVID-19 pandemic, we have seen simulations used to make decisions on the basis of the predictions they were able to produce. In this sense, the pandemic has raised the attention of the general public on an issue that has been routine for decades for the community of experts: the role of models and simulations to elaborate future scenarios and, as a consequence, to support political, technical and personal actions on the present (McLeod & McLeod, 1974; Schultz, 1974).

Even if the predictive character is an important feature of many computational simulations used in real-life problems, this issue is rarely addressed in science education. Indeed, most studies about the use of simulations in educational contexts focus on their explanatory character. Especially when complex systems are addressed, students are encouraged to use models and simulations to make-sense and derive explanations of the simulated emergent phenomena (Jacobson & Wilensky, 2006). Framed within the recent body of literature in future-oriented science education (Levrini et al., 2019; Levrini et al., 2021), in this module we address simulations as educational objects which can stimulate students' reflections on the future. The simulations involved in our teaching activities are not meant to *predict* the future perfectly or produce realistic pictures of the future (Reutlinger, Hangleiter & Hartmann, 2018). As in other future-oriented activities, the aim is rather to make students explore the mechanism to build a plurality of different scenarios, enhance their imagination on their personal future and the future of cities, countries and society and develop so-called future-scaffolding skills (Levrini et al., 2021) to navigate the complexity of these futures.

3. Research background

The data analysis presented in this chapter stemmed from what emerged in three previous studies, where students were engaged in similar future-oriented activities (Branchetti et al., 2018; Levrini et al., 2019; Tasquier et al., 2019; Levrini et al., 2021). The first two studies (Branchetti et al., 2018; Levrini et al., 2019; Tasquier, Branchetti & Levrini, 2019) were conducted with Italian students who described their experience as a process that led them to *widen* their views about the future and to feel the future as more *approachable*; moreover, they mentioned structural and dynamic skills that appeared to be good candidates for becoming recognizable as future-scaffolding skills. The latter (Levrini et al., 2021) is a study conducted during the international summer school of the I SEE project (www.iseeproject.eu) that involved 24 upper secondary school students from three schools of Iceland, Finland and Italy. In this study, we defined markers for recognizing operationally phenomena of changing in students' future perception and the development of future-scaffolding skills. In Table 1 and 2 we report the main results of that study, that are the operational descriptions of the markers for the change of future perception (widening and approaching) and for future-scaffolding skills (structural and dynamical) by using examples of students' expressions.

Table 1. Operational description of the markers for the change of future perception by using examples of students' expressions (Levrini et al., 2021).

Description of marker	Examples of students' sentences
WIDENING	
(Wid0) Widening in the amount of knowledge about the disciplinary contents of the FoSI (Future-oriented Scientific Issue)	The summer school made me better understand what we are talking about when discussing climate change, what the problems actually are. (SM23)
(Wid1) Widening in the amount of knowledge on future thinking, provided by futures studies	I thought it was very cool to be introduced to the idea of the three futures: the expected, the plausible and the preferred. I had not given this concept any thought before and the two lectures drove the point home exceptionally well. (SM12)
(Wid2) Widening in the range of new ways of addressing and looking at the FoSI	I've learned that the future is complex, and it has to be viewed from many points of view. I've learned to look at every topic from many different viewpoints and to think of many solutions for the future. This is something that is not taught at school that much, in my opinion. (SF4)
(Wid3) Widening in the range of possible roles of non-expert stakeholders (e.g. citizens, policy-makers) for addressing the FoSI	Everyone has to take care of global development. The world I want to live in includes a government that listens to sensible people who have important things and ideas to share. Everyone has to become aware of climate change and are living eco-friendly lives while trying to diminish the damage that was done in the past. (SF13)
(Wid4) Widening in the range of possible roles of expert stakeholders (STEM researchers and other experts in the field) for addressing the FoSI	You do not usually hear much about people who are active in environmental research. Now I know there are people working to improve this situation. (SF17)
(Wid5) Widening in the range of possible actions, strategies and concrete solutions that can be undertaken to address the FoSI	I've gotten to learn about some solutions I hadn't heard of before, for example I didn't know biofuel was an option. (SM9)

APPROACHING	
(Ap1) The future became closer to students' imagination, i.e. from far and unimaginable, it became thinkable to them	Now when I think of the future, I see a beautiful sunset. It's such a beautiful word and the three horizons, it makes them all beautiful. (SF10)
(Ap2) The future became closer to students' present reality, i.e. it became approachable through concrete actions that can be undertaken in the present	Perhaps I will in general consider what I do […] Because I got to know how big my carbon footprint is. So maybe I'll think of my everyday choices more and how to do things better. (SF2) I'm interested in taking action to protect the environment. For example, I'd like to minimise the amount of food waste. (SF4)
(Ap3) The future became closer to students' personal, social, professional growth path, i.e. it became within their reach and they found ways to see themselves as agents of their own future	This showed me, opened up a door for me. I always wanted to go into this field, but now I know I can. It increased the chances for me that I go into STEM. (SF13)

Table 2. Operational description of the markers for the future-scaffolding skills by using examples of students' expressions (Levrini et al., 2021).

Description of marker	Examples of students' sentences
STRUCTURAL SKILLS	
(St1) Distinguish between disciplinary details and the comprehensive picture of the FoSI	Each experiment added a piece of knowledge that at the end of the path of the experimentation occurred to recreate the complete picture of the situation. (SF17)
(St2) Unpack the FoSI in simpler, addressable parts	I have learned that if you want to achieve something it is good to divide it [the task] in smaller pieces. (SM1)
(St3) Recognize causal relationships	I found helpful these activities […] because they made me understand suddenly the reasons beyond the feedback process. The biofuel activity in my opinion really worked because we got into the process that involved considering the consequences in the future as the main task. (SF19)
(St4) Recognize multiple aspects of the problems and their relationships (e.g. distinction between problems, objectives, solutions or between pros and cons) for structuring proper thoughts and articulate strategies and plans for solving them	The biodiesel issue has positive and negative aspects: we have to consider both of them. It involves ethical, social and political issues. […] I think future revisioning, problem analysis and calculating carbon sequestration are really helpful activities to have a complete view of the dimension of a problem, and to start thinking about the solutions and not only about the effects. (SF19)

DYNAMICAL SKILLS	
(Dyn1) Move from thinking locally to thinking globally (and vice versa)	We really need to think globally, even though we start with ourselves and our cities, our countries. (SF15) We should always take into account that global conditions affect local conditions, so everyone should care about the whole global development. (SF19)
(Dyn2) Move from thinking at the present to thinking at the future (and vice versa)	In the future, but starting from now, we will make a choice about what kind of society and cities we want to live [...] Be careful with alternative fuels or other kinds of natural energy sources: look at their impact on the environment as far in time as you can. (SM23)
(Dyn3) Move from thinking at the individual to thinking at the societal community and/or the other stakeholders	Everybody should just realize that we need to cooperate. We are not going to succeed if there are only a couple of people. (SF2) When I have thought about the future, I have always just seen myself. I have never thought about the people around me or what is happening around me. (SF10)
(Dyn4) Think creatively for imagining new possibilities and concrete actions	They got the group to use everyone's imagination and come up with all sorts of ideas. It also got us to think critically and try to find plausible solutions to current environmental problems, which was good. (SF13)
(Dyn5) Balance the need of aspiring and desiring with that of keeping feet on the ground	I know now that it is alright to dream big, these things are happening in real life, real days but yeah we still have a long way to go and I realized that I thought a lot about changes we needed to make in the world but not about how we make those changes, how we change all the things that are bad. (SF15)
(Dyn6) Think in a multidisciplinary way, breaking down the barriers among disciplines	Humanistic and technological aspects were very intertwined ... ethics was interspersed with technological development. (SF19) It was also a brilliant example to see that in the world of jobs you need to develop transversal skills, you can no longer be too attached to the 'engineer', for example, and be just an engineer. You need to be able to collaborate with various experts and be able to understand and help them. (SM22)
(Dyn7) Move from thinking in terms of necessity to thinking in terms of multiple possibilities	I always get really stressed when I think about the future, just what I am going to do in the future, but thinking like this, because I had never realized, I have always thought about maybe one scenario that could happen, which is often one in which everything falls apart totally, but to think from the perspective of many possible futures, like the cone and the models even for what could be outside of the cone. There is so much that could happen. I thought that was really interesting. Just to think of all the thinkable (possible) possibilities, find the most likely, but still, you know, to think of the most unlikely because there are still chances that they could happen, too. (SF10)

In the study by Levrini and colleagues (2021) we observed that, through the module on climate change, most students experienced a widening of possible ways of thinking, roles of stakeholders, and actions to address the future-oriented scientific issue at stake. Moreover, they perceived the future as approaching them, since it became closer in their imagination, their present and their growth path. In particular, six different nuances of widening and three of futures approaching where identified, as reported in Table 1.
Moreover, the students were able to develop through the module a set of skills that we organized in two macro-categories. The four structural skills are abilities to organize pieces of knowledge and build systemic views (an intentional and conscious process of scaffolding) while the seven dynamical ones are abilities to navigate across the complexity of knowledge, without trivializing the relations between local details and global views, the relations between past-present-future, and the role of individual and collective actions. These skills were named and recognized as future-scaffolding skills since the structural ones build a rational scaffolding of the topic by recognizing the causal, temporal, and logical relationships among them while the dynamical skills allow to navigate across the scaffolding for developing scenarios, visions, and creative ideas for the future (Levrini et al., 2021, p. 21).

4. The module

The principles described in Section 2 were at the basis of the design of the module proposed to upper secondary school students. They not only constitute the basis for the development of the module but were made explicit with the participants in order that they could actually reflect on these issues.
We recall that the module on simulations of complex systems was part of the educational offer of the Department of Physics and Astronomy of the University of Bologna for university orientation of high school students within the PLS program. For the issues addressed, the module was also part of the outreach activity of the Open Physics Hub project (www.site.unibo.it/openphysicshub/en), aimed at promoting excellence and innovation in all the activities of the Department, with specific attention to the field of sensing and computation for modelling, simulations, and data analysis of various physical processes. For the focus on the interdisciplinary character of simulations, as argued in section 2.1, the module was also organized with the collaboration of the Erasmus+ project IDENTITIES (www.identitiesproject.eu) that has the goal of developing teaching-learning modules for preservice STEM teachers on interdisciplinary topics; the module for secondary school students can be considered a pilot of future adaptation and implementation with teacher-students.
In this section we provide a description of the module. An overview of the overall module's structure with its six lectures of three hours each is reported in Table 3.

Table 3. Overview of the structure of the module on simulations of complex systems.

Lesson	Title
Lesson 1	*Lectio magistralis*: "Computational physics in the era of big data"

Lesson 2	Ice-breaking activity and round table with early career researchers: “Simulations as research tools”
Lesson 3	Interactive analysis of agent-based simulations of complex systems
Lesson 4	Activity of analogies’ development: “From models of systems to real problems”
Lesson 5	Group activity of construction of scenarios based on simulations
Lesson 6	Groups’ presentations and conclusion

4.1. Lesson 1 – *Lectio magistralis*: “Computational physics in the era of big data”

The first lesson of the module was held by Prof. Daniele Bonacorsi, full professor of experimental physics at the Department of Physics and Astronomy. The goal of this lecture was to situate the simulations in the wider panorama of the computational physics (and computational science in general). From a conceptual point of view, this first lecture aims at pointing out that:

- simulations are one of the three pillars of contemporary scientific research, together with experimentation and theory;
- they can be defined in a technical sense as programs run on a computational resource which is based on algorithms and processes executed step-by-step to reproduce approximately the behavior of a “natural” system under study;
- different types of simulations exist, like the equation- and agent-based ones, as well as the Monte Carlo “simulations” that have an outstanding importance in physics even if not all authors agree on their authentic character of simulations;
- a simulation can have multiple objectives: from heuristic goals (communicate knowledge to others or represent knowledge to us) to explanation and prediction aims;
- simulations play such an important role in the process of scientific discovery that an analogy can be constructed between simulations and experiments (Jebeile, 2017): they both allow to: 1) explore and intervene on the evolution of a system changing initial conditions or parameters, 2) to visualize a phenomenon contributing to its interpretation, 3) to generate new knowledge. A fourth point, more articulated from an epistemological point of view is the “black box” character that both complex experiments and simulations share, for the practical impossibility of surveying analytically all the processes they embed (Dowling, 1999, p. 266);
- the increasing involvement of modelling and simulations tools in scientific research is strictly connected with the big data outbreak, from the data pipeline to the use of supercomputing and various computational resources and paradigms, passing through data-driven models, artificial intelligence and machine learning;
- nowadays, the design and development of a simulation that works on Big Data uses enormous computational resources and requires profound knowledge of computing models and infrastructures (CPU, storage techniques, networks, databases, computing paradigms).

The lecture ended by stating how simulations are the protagonists of an unprecedent transformation of the method of scientific discovery. In this process of change, disciplines contaminate each other and transform themselves, and this open evolution of knowledge is in the hands of future physicists, scientists and professionals who will research in these fields.

4.2. Lesson 2 – Ice-breaking activity and round table with early career researchers: "Simulations as research tools"

The second lesson of the laboratory was divided in two parts: i) ice-breaking activity and ii) round table with early career researchers.
The ice-breaking activity was aimed at making students know each other and start reflecting on the three "red threads" of the course: future, interdisciplinarity and the intertwining between science and society. Concretely, after introducing themselves and their expectation for the course, the students were divided in groups and had to fill a shared Google Jamboard as that in Figure 1. Focusing on the three threads, they had to explain if and how they were interested to those issues and why, in their opinion, simulations were related to them.

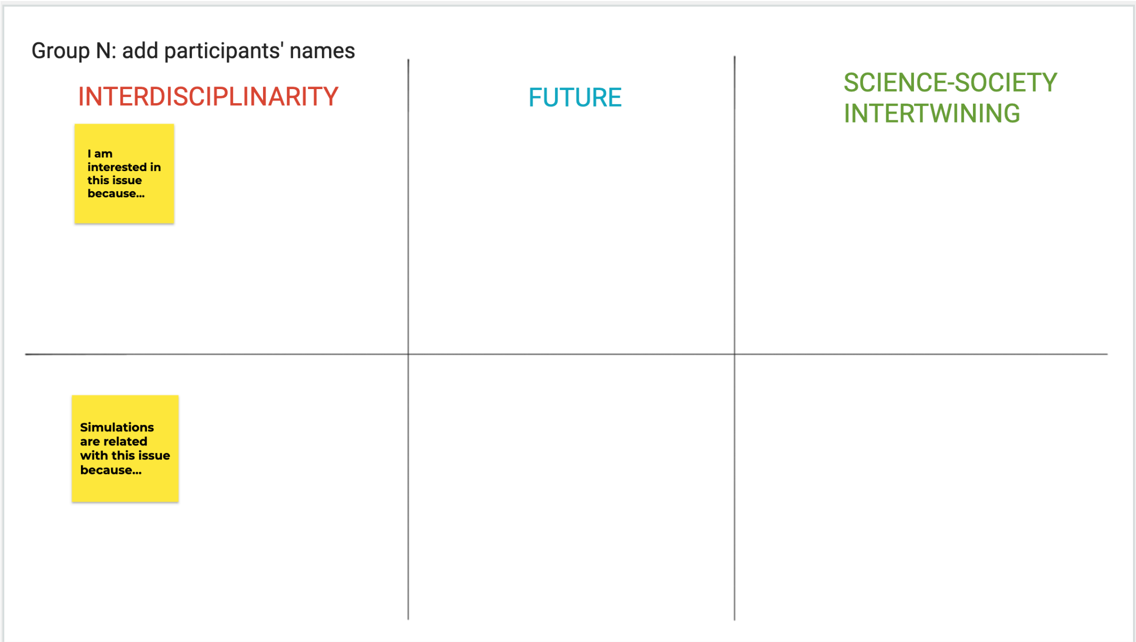


Figure 1. Shared Google Jamboard for the ice-breaking activity

After 15 minutes of work in little groups, the spokesperson of each group had one minute to summarize to all participants the central idea of the discussion that occurred.
The second part of the lesson was a round table in which 3 Ph.D. students and 2 early career researchers of the Department of Physics and Astronomy took part describing their research experience with simulations in different fields of physics and astronomy. The goal of this moment was to enrich students' imagination about the frontiers of physics research involving computational simulations and also orient students to the university choice. We briefly present the core of the five speeches:

- Dr. Leonardo Aragão (post-doc researcher) presented his work in the field of climatology to develop weather forecast models. Here, equation-based simulations are written according to the physical laws that govern the main flow in the atmosphere (momentum, mass and energy conservation) and can be used to predict phenomena on global, regional or mesoscale levels with different time ranges, from nowcasting (forecasts up to 2 hours) to climate models (with prognosis usually over 2 years). To exemplify these notions, Dr. Aragão presented a retrospective simulative study to model the extreme events observed at the Emilia-Romagna coast (Italy) in 2015.

- Matteo Billi (Ph.D. student) presented the role of simulations in cosmology, and in particular in the study of the cosmic microwave background. He showed how, in cosmology in general and in his research activity, simulations play a role in the design of experimental apparatuses, when they model the response of the experimental tools, and in the statistical analysis of data, with Monte Carlo simulations. Providing examples for these two roles of simulations in astrophysics, he showed that cosmological simulations are a fundamental element in the construction of theory that in turn allows an interpretation of the experimental observations.
- Francesco Durazzi (Ph.D. students) allowed the students to see an application of simulations in the field of epidemiology. Starting from the difference between deterministic equation-based models and agent-based simulations, he addressed the concrete example of the transmission of bacteria in a hospital ward to make explicit the distinction betwen the two approaches. Showing the graphics for the number of uncolonized, sensitive and resistant patients and nurses according to the deterministic equation-based model and the agent-based simulations, he argued how the simulation gives on average the same results of the deterministic model but also returns a confidence interval that indicates the accuracy of the prediction. Indeed, while the deterministic model does not distinguish the characteristics of the individuals, in the agent-based simulations each agent can have their own features and interactions with other, defining the agent's contact network.
- Dr. Silvia Biondi (post-doc researcher) showed to the students the uses of simulations in particle physics, with particular reference to the ATLAS experiment at CERN'S LHC (Geneve, Switzerland). The Monte Carlo simulators allow to generate data for the expected collisions occurring in the accelerator. These simulated data are then compared with real data and contribute to distinguish background processes and signal events. Hence, simulations have a huge role in the process of scientific discovery, since they show how much the results of an experiment differ from the theoretical expectations given, for example, by the Standard Model. She also presented the case of the Higgs' boson discovery as an example of scientific discovery in which Monte Carlo simulations had a crucial role.
- Carlo Emilio Montanari (Ph.D. student) presented a different use of simulations in particle physics, that is the design and construction of accelerators. Nowadays the construction of high-energy accelerators is a complex challenge that involves, for example, engineering limits (for the electric and magnetic fields that can be produced) and a huge budget. In this process, the contribution of simulation techniques to the design of these machines is enormous. Specifically, he presented his specific area of expertise that consists in simulating the dynamic of protons in an accelerator, testing mathematical models to improve the predictions of stability.

At the end of each intervention, a short time was left for clarification questions from the audience. After the five presentations, the students could ask more general questions to the panelists.

4.3. Lesson 3 – Interactive analysis of agent-based simulations of complex systems

The third lesson of the course was the core lecture in which the students were guided to explore first-hand some simulations of complex systems. Basing on the distinction between equation- and agent-based approaches – already introduced in lesson 1 – in this lecture was presented the Lotka-Volterra model an emblematic case study to see in detail the difference between the two types of modelling. Then, focusing on the agent-based approach, other models and simulations of complex systems were presented, the voter and cooperation models. For each model, the relative simulation from the NetLogo Models Library was presented and questions were asked to the students to make hypothesis on the expected behaviors or to formulate explanations. The choices to treat the models and simulations in the lecture were based, when available, on research results in science education and particularly on the work by Wilensky and Reisman (2006). We present each model underlying the main conceptual and epistemological issues raised.

4.3.1. The Lotka-Volterra predator-prey model and its simulation

Presenting the predator-prey model (Volterra, 1926), we aimed at raising the following conceptual points:

- to understand a model, we need to clarify the hypotheses on which it is based; in the case of the Lotka-Volterra model, we have two species (the preys and the predators) in which the preys have unlimited food, the predators are fed only eating preys, the preys only die by natural death, there are not on-going evolutionary mechanisms, the external environment do not change in favor of none of the species;
- two first-order differential equations can be written to describe the time evolution of the rate of increase or decrease of the preys' and predators' populations:

  $$\frac{dx(t)}{dt} = ax(t) - by(t)x(t)$$
  $$\frac{dy(t)}{dt} = cx(t)y(t) - dy(t)$$

  where x(t) represents the number of prey at the instant of time t and similarly y (t) represents the number of predators at the instant t; consequently the time derivatives of these quantities represent the rate of change of prey and predators respectively over time. The coefficients a, b, c and d instead quantify the birth of prey (a) and predators (c) and the death of prey (b), due exclusively to predation, and the natural death of predators (d). We can observe that the first equation of the system has two terms: the first in which the birth coefficient of the prey is multiplied by the number of prey at instant t, contributing positively to the increase in the number of prey at the next instant; the second term (-bx(t)y(t)) determines the decrease in the number of prey due to the phenomenon of predation, this term depends on the number of interactions that occur between prey and predators, in turn proportional to the product between the two populations at time t (x(t)y(t)). The second equation instead describes the trend of the predator population over time; it also consists of two terms, whose analysis is similar to the previous one. However, in this case, the birth of predators depends on the frequency of interactions between the two species while the mortality rate of predators is independent of the number of preys (as in the model's hypotheses, predators only die by natural death), as opposite to the death term of the first equation;

- if the differential equations are numerically solved, a stable periodic solution is obtained, showing the cyclic evolution in the number of preys and predators, as shown in Figure 2;

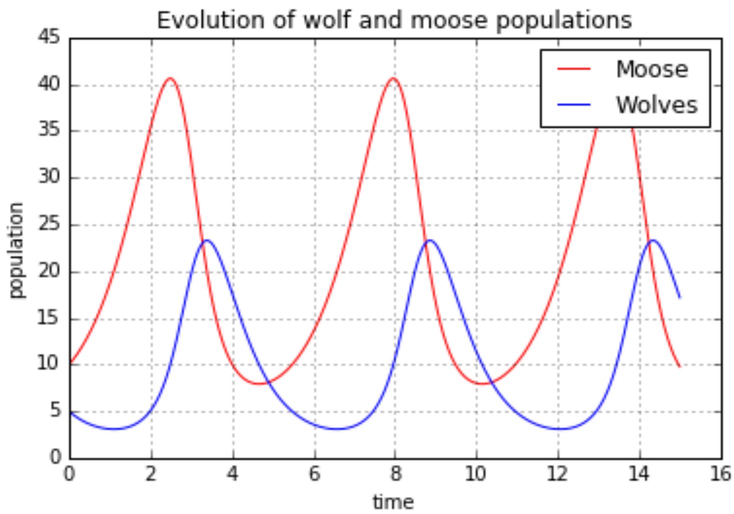


Figure 2. Results of the numerical solution through an equation-based simulation for the number of predators (wolves) and preys (moose) using the Lotka-Volterra differential equations.

- the results of simulations can be compared with those of a very significant case study carried out in the 1950s on the Isle Royale (Michigan, US) concerning the predation phenomenon involving moose and wolves (Peterson & Page, 1983; Peterson, Page & Dodge, 1984). Even if this case study seemed particularly suitable for the comparison with the theoretical model, comparing the simulated data of Figure X and the real observations of Figure 3 we can notice only partial adherence with the theoretical model. This is mainly due to two phenomena. Indeed, around the 1980s, the sudden decrease in wolves was inadvertently caused by humans who brought to the island a virus that decimated the wolf population. Moreover, in the following period, a series of very cold winters suddenly decreased the food resources of the moose, whose population resulted considerably reduced;

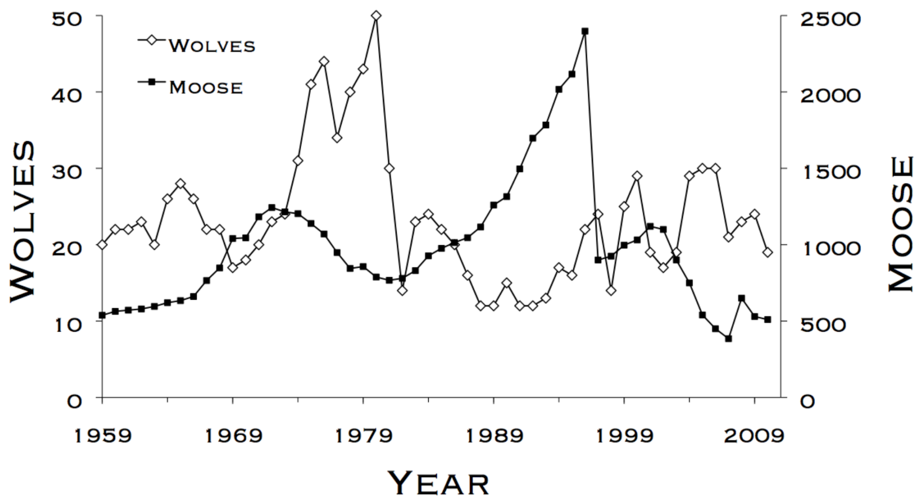


Figure 3. Observational data for the number of preys and predators on Isle Royale between 1959 and 2012. 1959-1964: After observing relatively constant abundances for five years, it seemed that the wolves and moose of Isle Royale had struck some kind of a balance of nature. 1964-1972: Over time wolf abundance fluctuated a bit. But, after a series of mild winters moose abundance doubled. There'd been a major shift in the balance. 1972-1980: Then a series of severe winters, increased wolf predation, and moose abundance was cut in half. Wolves soared to 50 individuals. 1980-1982: Humans inadvertently introduce canine parvovirus, a wolf disease. The wolf population crashes. 1982-1996: With a reprieve from wolf predation, the moose population explodes. We begin to think, but cannot yet prove, that inbreeding among wolves explains why they languor in low abundance for over a decade. 1996-1997: Intense competition for a declining forage, an outbreak of winter ticks, and the severe winter. They all conspired against the moose population which collapsed in 1996. Moose continue to dwindle. 1997-2006: In 1997, a wolf immigrates from Canada, bringing an infusion of new genes. The wolves increase erratically. 2006-2012: The wolf population eventually stumbles as the moose continue to be kept low by high rates of predation, ticks, and hot summers. (www.isleroyalewolf.org)

- an agent-based model can be constructed assigning different rules to preys and predators. In particular, we can imagine a system of wolves and sheep in which each wolf:
    - starts its life with a random amount of energy;
    - at each tick of the simulation, it moves to an adjacent cell and its energy decreases by E1;
    - if there is a sheep in the same patch, it eats it and its energy increases by E2;
    - when the energy reaches 0, the wolf dies;
    - at any given moment, it has an R1 chance of reproducing.

  While each sheep:
    - at each tick, it moves to an adjacent patch;
    - at any given moment, it has an R2 chance of reproducing;
- a comparison can be outlined between the equation- and agent-based approaches to the modelling of the predator-prey interaction. While in the equation-based model there are only macroscopic quantities (e.g. total number of the preys or predators at a given time), in

the agent-based model we focus on the single agent (the single prey and the single predator) that obeys specific behavioral rules. Moreover, while the equation-based modelling is deterministic, de agent-based one is probabilistic since in its formulation is embedded the concept of probability. For a more detailed analysis of this distinction, we refer to Chapter 5. The behavioral rules of the agents can be traced in the code of the NetLogo Wolf Sheep Predation simulation (Wilensky, 1997a). The correspondence between rules and code is shown in Table 4.

Table 4. Correspondence between the rules of the predator-prey agent-based model and the code of the NetLogo "Wolf Sheep Predation" (sheep-wolves variant) simulation (Wilensky, 1997a).

	Code	Pseudocode
Wolves' rule	ask wolves [move set energy energy -1 eat-sheep death reproduce-wolves]	At teach tick of the simulation, each wolf is asked: - to move to an adjacent patch, - to decrease its energy of 1, - to evaluate the possibility of eating a sheep, - to evaluate the possibility of dying, - to evaluate the possibility of a reproduction.
	to move ; rt random 50 lt random 50 fd 1 end	To move, the wolf: - turns right by a random degree between 0 and 50, - turns left by a random degree between 0 and 50, - moves 1 step forward.
	to eat-sheep ; let prey one-of sheep here if prey != nobody [ask prey [die] set energy energy + wolf-gain-from-food] end	To eat a sheep, the wolf: - checks if there is a prey in its same location, - if there is a prey: - the prey dies (ceases to exist), - the energy of the wolf is increase by the value expressed by the wolf-gain-from-food parameter.
	to death ; if energy < 0 [die] end	To die, the wolf: - dies (ceases to exist) in case its energy is below 0.
	to reproduce-wolves ; if random-float 100 < wolf-reproduce [set energy (energy / 2) hatch 1 [rt random-float 360 fd 1]] end	To reproduce, the wolf: - "throws a dice" to see if it is going to reproduce in that moment (if the random generated number is below the reproduction chance expressed by the wolf-reproduce parameter), - in case the reproduction is allowed: - the energy of the wolf is halved, - 1 new agent is created, and it randomly chooses its direction and moves 1 step forward.
Sheep's	ask sheep [move reproduce-sheep]	At each tick of the simulation, each sheep is asked: - to move to an adjacent patch (as seen for wolves) and - to evaluate the possibility of a reproduction.
	to reproduce-sheep ;	To reproduce, the sheep:

	if random-float 100 < sheep-reproduce [hatch 1 [rt random-float 360 fd 1]] end	- "throws a dice" to see if it is going to reproduce in that moment (if the random generated number is below the reproduction chance expressed by the sheep-reproduce parameter), - in case the reproduction is allowed, 1 new agent is created, and it randomly chooses its direction and moves 1 step forward.

- running the simulation with these rules, the system shows only a transient phase of oscillations between the populations. Differently from the equation-based model where the solution was periodic, in the agent-based model we observe two possible behaviors: or the number of preys increase exponentially (Figure 4, left), or both populations of preys and predators end to become extinct after few oscillations (Figure 4, right). As pointed out by Wilensky and Reisman (2006), this apparently wrong result is actually in line with the findings of the first laboratory experiments on the predator-prey interaction, carried out between two species of competitive unicellular organisms (Gause, 1934): or the predators ate all the prey for then die of hunger, or the predators died first, and the prey multiplied excessively;

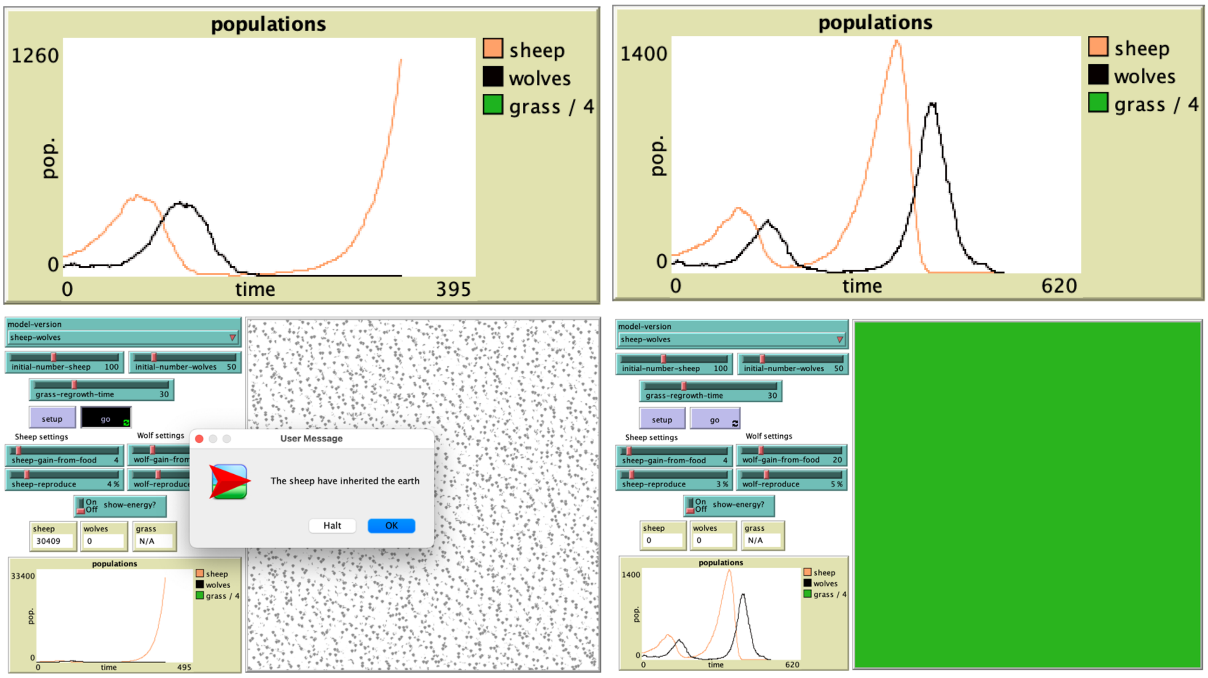


Figure 4. Results of the agent-based NetLogo simulation "Wolf Sheep Predation" (sheep-wolves variant) with the same default set of parameters (Wilensky, 1997a). On the left side, the graph (top) and the grid (bottom) showing the unlimited growth of the prey population. On the right side, the extinction of both populations is obtained.

- The unexpected behaviors can be explained reflecting on the differences between the Lotka-Volterra model and the natural environment it was supposed to model and between the agent-based simulation we have discussed and laboratory experiments. In the laboratory, just like in the last simulation, there are no limits to the growth of the prey population and there is no environmental complexity (the prey cannot escape predators by taking refuge in a certain area of the environment). Therefore, the agent-based simulation, by omitting these two factors, replicates and correctly predicts the population trend observed in the laboratory. However, even the Lotka-Volterra model was based on the same assumptions, but the solutions of its equations are stable and reproduce the real-world behaviors and not the laboratory one. It could seem a paradox. As pointed out by Wilensky and Reisman (2006), compared to agent simulations, classical equation models make it very easy to obtain implausible macroscopic results. Indeed, in modelling with a top-down equation-based approach, the focus is on the desired output (the stability of solutions, in this case), while in the agent-based bottom-up approach the rules are assigned to the agents without making any assumptions on the macroscopic level. Hence, it is possible that no local rules exist to produce the stability result which is predicted by the equation-based model.

- To make the simulation closer to the real phenomenon we can include in the system a limit for the growth of the prey, that is, we can introduce in the system of food resources for the prey that take some time to regenerate after being consumed. In doing so, the prey will no longer die exclusively from predation but also from natural causes (lack of food). While the rules for the wolves remain the same as before, the rules for the sheep are modified as follows. Each sheep:
    - starts its life with a random amount of energy;
    - at each tick, moves to an adjacent cell and its energy decreases by E3;
    - if there is grass in the same patch, it eats it and its energy increases by E4;
    - when the energy reaches 0, the sheep dies;
    - at any given moment, it has an R2 chance of reproducing.

  The grass grows and regenerate at rate specified by a time parameter. The behavioral rules are implemented in the “Wolf Sheep Predation” NetLogo simulation (sheep-wolves-grass variant) with similar functions as those in Table 4.
- By adding the grass-related rules to the simulation, stable and periodic oscillations are obtained between for the quantity of prey, predators, and food resources, in line with what can be observed in nature. It is also noted that by limiting the resources of the prey, their chances of survival are increased (enrichment paradox). The graphical results are displayed in Figure 5.

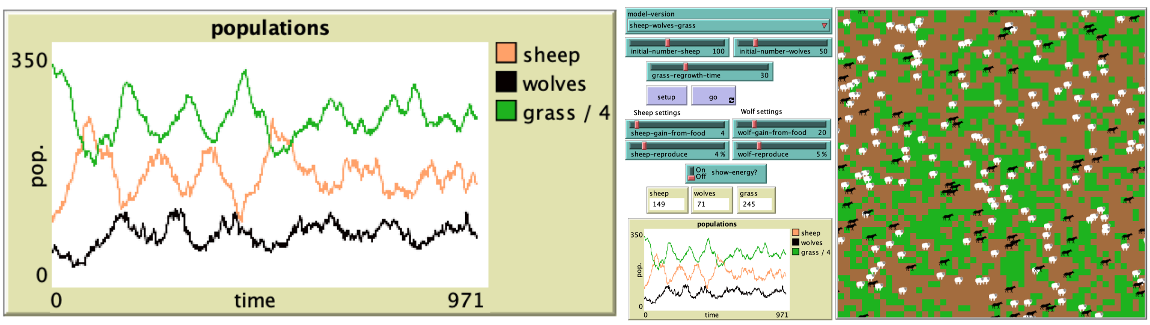


Figure 5. Results of the agent-based NetLogo simulation “Wolf Sheep Predation” (sheep-wolves-grass variant) with default set of parameters (Wilensky, 1997a).

From the epistemological point of view, the articulated presentation of the predator-prey model has allowed to point out that:

- to formulate each model and to allow a sensible interpretation of its results, it is important to clearly state the assumptions on which it is based;
- equation- and agent-based approaches differ on many levels, mainly their top-down and deterministic character of equation-based simulations versus the bottom-up and probabilistic nature which characterizes agent-based simulations;
- from the qualitative description of the rules of the model follows the computational implementation of the algorithm at the basis of the simulation;
- the epistemological and conceptual differences between the two approaches can be traced directly in the code of the simulation, which the students are guided to read and interpret even without a programming background;
- different models can be expressed with a different type of mathematics: the equation-based approach shows the example of continuous differential equations, the agent-based approach illustrates the case of the use of discrete and threshold-based descriptions;
- models, experiments, and real-world phenomena can live in intricate relationships, as shown by the comparison of equation- and agent-based simulations of the predator-prey interaction. Recognizing the structural features of both of them can help explaining and making sense of possible unexpected simulated behaviors.

During the lecture the students were asked two answer two questions on a shared Google Jamboard. The first was asked after showing the solutions of the equation-based models, before passing to the agent-based description: *What rules should individual predators and individual prey follow to give the observed oscillating result?.* The second question instead concerned the hypothesizing of an explanation for the unstable behavior observed with the first variant of the agent-based simulation (without grass): *The set of rules we have set gives rise to unstable behavior where sheep increase exponentially and wolves go extinct. Why does this happen? How do we "stabilize" it?.*

4.3.2. The voter model and its simulation

After having discussed the difference between equation- and agent-based approaches to simulations with the case study of the predator-prey model, the following part of the lesson only addresses agent-based simulations. The next model presented is the voter model for opinion dynamics (Clifford & Sudbury, 1973; Holley & Liggett, 1975). It is the basic version of the Axelrod model for the cultural interactions presented in detail in Chapter 6. During the lecture, we aimed at raising the following conceptual points:

- the dynamics and change of opinion within a social group can be modelled representing an opinion as a characteristic that each individual possesses and that can change as a result of interactions with other individuals and with the outside world. In particular, an opinion can be modelled as a binary quantity: it can assume only two values (0 or 1, true or false, spin-up or spin-down, blue or green, etc.);

- even if different formulations are possible (Castellano, Fortunato & Loreto, 2009)[21], the dynamic of change of opinion can be described with the following behavioral rules, applied to each agent of the model. When an agent is selected:
    - it counts the number of neighbors with its same opinion and with different opinions;
    - it changes its opinions following the majority;
    - in case of a tie, it does not change its opinion;
- these rules can be implemented in a NetLogo simulation as the "Voter" one, available in the Models Library (Wilensky, 1998). The analysis of the code related to the agents' behavior is reported and commented through pseudo-code in Table 5.

Table 5. Correspondence between the rules of the voter model and the correspondent NetLogo "Voting" (sheep-wolves variant) simulation (Wilensky, 1998).

	Code	Pseudocode
Agents' definition	patches-own [vote total]	Each agent is defined has having two variables: - its vote (that can be 0 or 1), - the sum of the votes of the neighbors around it. The value of the two variables will change as the run of the simulation advances.
Agents' rules	to go let any-votes-changed? False ask patches [set total (sum [vote] of neighbors)] ask patches [let previous-vote vote if total >= 5 [set vote 1] if total <= 3 [set vote 0] if vote != previous-vote [set any-votes-changed? true] recolor-patch] if not any-votes-changed? [stop] tick end	For each agent - the variable "total" is updated with the sum of the neighbors' votes, - the present vote of the agent is stored (in the "previous-vote" variable), - if "total" is greater than or equal to 5, the vote of the agent is set to 1 (as the majority of the neighbors), - if "total" is less than or equal to 3, the vote the vote of the agent is set to 0 (as the majority of the neighbors), - if the agent has changed its opinion, the colors of the agent is changed accordingly (0 votes are colored green, 1 votes are colored blue). The process goes on until we arrive at an iteration in which no agents change their opinions.

- Starting from an approximately equal but random distribution of blue and green patches, when the simulation is run with these rules, we obtain a stable situation characterized by the formation of clusters of patches with the same opinion, spatially close to each other. This behavior is shown in figure 6. Jack, Feyereisen and Thielen (2021) demonstrate how if the initial proportions of the two opinions are equal, it takes an indeterminate number of

[21] An alternative description of the model consists, for each selected agent, in choosing a random neighbor and taking its opinion. The difference with the case presented in the thesis is that the selected agents "feel the pressure of the majority of their peers only in an average sense: the state of the majority does not play a direct role and more fluctuations may be expected with respect to the zero-temperature Glauber dynamics" (Castellano, Fortunato & Loreto, 2009, p. 9).

steps to reach an equilibrium, at which, on average, we have the same proportions as at the beginning. However, clusters are always observed.

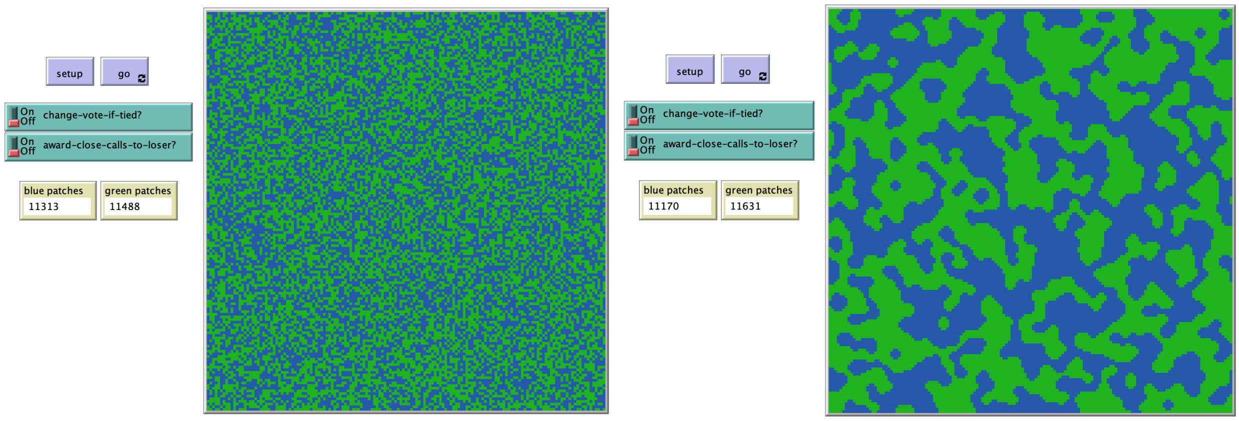


Figure 6. Initial (left) and final (right) configuration of the system of agents with the NetLogo Voting model (Wilensky, 1998).

- This simple model can be enriched adding variants. For example, that named "change vote if tied", wants that in case of a tie the agent always changes its opinion. Applying this rule, a similar situation to that of Figure 6 is obtained, but with oscillations at the edges, as we try to report in Figure 7. For the dynamic visualizations, we recommend running the simulation in NetLogo (Wilensky, 1998).

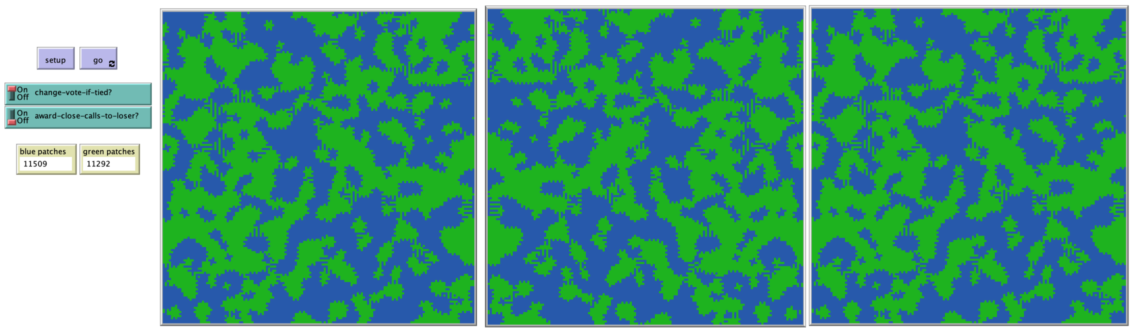


Figure 7. Three consecutive ticks of the NetLogo Voting simulation (change-vote-if-tied variant) (Wilensky, 1998).

- The reason for the oscillations that are observed at the boundaries between clusters can be found in the local mechanism of interaction of the agents. If we look closer to the behavioral rules in case of a tie, with the variant we have a continuous "flip" of the agent's opinion. Indeed, if none of its neighbors is changing opinion, there is a continuous transition between the two values (or colors), as schematically represented in Figure 8;

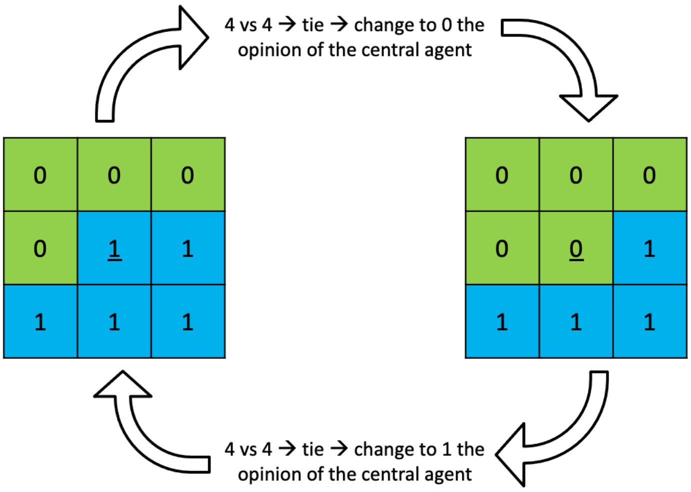


Figure 8. Graphical microscopic explanation for the oscillating behaviors observed at the boundaries of clusters obtained with the NetLogo Voting simulation (change-vote-if-tied variant).

- the voter model, with its description of changing of opinions, is widely used in the social sciences. However, the dynamics of the change of opinion are very similar to that of the physical phenomenon of magnetization which can be described by a model based on similar rules: the Ising model. At the microscopic level, a magnet is model as a spin lattice, each of which can be in an up or down state and is influenced by the behavior of the neighbors. The difference between the number of spin up and spin down gives the total magnetization of the system, observable macroscopically. Depending on the temperature, there can be different phases of the magnet. At low temperatures the system is in the ferromagnetic phase, a phase in which the spins tend to align themselves spontaneously (Figure 9, top); at high temperatures there is no spontaneous magnetization, and the system is in the paramagnetic phase (Figure 9, bottom).

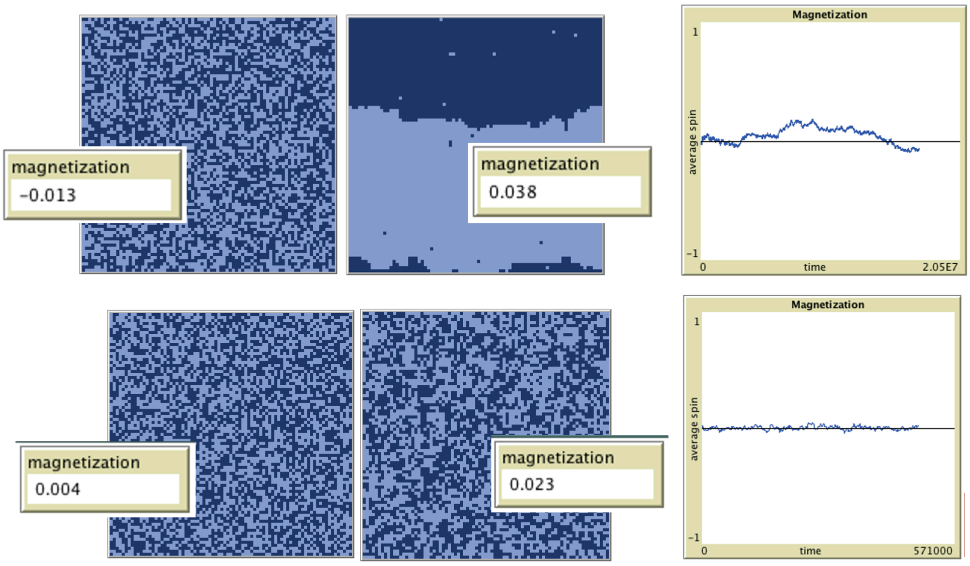


Figure 9. Initial (left) and final (right) configuration of the Ising model implemented in NetLogo (Wilensky, 2003). At the top, the ferromagnetic case; at the bottom, the paramagnetic case.

From an epistemological point of view, the articulation of the presentation of the voter model, allowed us to point out that:

- social phenomena like the change of voting preferences in a population can be modelled through a simple agent-based simulation;
- behind the model of opinion dynamics embedded in the voter model there is a physical model of interaction that comes from the Ising model of magnets. Thanks to its simplicity and abstractness, it is used as a basis for describing other physical (such as, for example, the phase transitions of a gas) or social phenomena in which agents are influenced by the state of the majority of their interacting partners (Castellano, Fortunato & Loreto, 2009, p. 4);
- the formation of clusters and the ability of an object to become magnetized, respectively in the Voting simulation and in the Ising model, are emergent properties of the complex system that are visible only on a macroscopic scale but depends non-linearly on the actions of the individual agents;
- in the Ising model we can find an example of interdisciplinarity between physics and social sciences because physics with its models (in our case, the Ising model) gives an interaction mechanism which in turns becomes a model to describe other contagion phenomena in other fields (Vespignani, 2019).

During the presentation of the voter model, the students were asked two answer two questions on a shared Google Jamboard. The first was asked after the introduction of the rules at the basis of the agent-based simulation on the voter model and required the students to think at possible configurations of the system following these rules: *What do we expect to happen in a system where each agent (with opinion 0 or 1) acquires the opinion of the majority of its neighbors?.* The second question was aimed at making students experiment with the emergent behaviors of the NetLogo Voting simulation and try to explain the observed results: *Experiment with the "voting" simulation: what behaviors do you observe? Concentrate on explaining why the different macroscopic configurations.*

4.3.3. The cooperation model and its simulation

The third and last simulation presented to the students regarded a model for cooperative behaviors. For what concerns the conceptual issues, during this part of the lectures we aimed at pointing out that:

- cooperation is an evolutionary mechanism, much studied in biology and the social sciences, in which different types of agents compete to obtain the same resources. Obtaining these resources determines their evolutionary success;
- an agent-based model for the description of cooperative behaviors can be developed considering two kinds of agents. Each agent's type consumes resources of the environment with a different strategy:
    - the cooperative agents consume resources only if they are in quantity greater than a given threshold;
    - the greedy agents consume resources regardless of their abundance.

For both types of agents:

- o the more the agents eat or access to resources, the higher is their probability of reproducing by generating agents which will follow the same strategy.

The two strategies differ because of another rule which is imposed to the resources of the system:

- o under normal conditions the grass has a given growth rate,
- o if the quantity of resources is lowered below a certain threshold, the speed with which they regenerate decreases. The more the agents feed, the higher their probability of reproducing by generating agents with their own characteristics (same strategy).

- basing on the previous rules, an agent-based simulation can be implemented. We considered the NetLogo "Cooperation" simulation, available in the NetLogo models library (Wilensky, 1997b) in which there are greedy and cooperative cows who compete for the same resource (grass) in a simulated environment. The analysis of the main portions of code related to the agents' behavior is reported and commented through pseudo-code in Table 6.

Table 6. Correspondence between the rules of the cooperation model and the correspondent NetLogo "Cooperation" simulation (Wilensky, 1997b).

	Code	Pseudocode
General procedure	to go ask turtles [move eat reproduce] ask patchs [grow-grass color-grass] tick end	At any tick of the simulation: - each cow has to: - move to an adjacent patch (similar to the code commented in Table 4 for predator-prey simulation), - decide if eating, - evaluate the possibility of reproducing (similar to the code commented in Table 4 for predator-prey simulation). - each patch containing grass has to: - decide if growing, - color themselves (similar to the code commented in Table 5 for voting simulation).
Resources' consumption rules	to eat ifelse breed = cooperative-cows [eat-cooperative] [If breed = greedy-cows [eat-greedy]] end	To eat: - the cooperative agents have to eat cooperatively; - the greedy agents have to eat greedily.
	to eat-cooperative if grass > low-high-threshold [set grass grass – 1 set energy energy + grass-energy	To eat cooperatively, the cooperative agents: - check if the level of grass is greater than a threshold:

	] end	- if so, the height of grass diminishes of 1 and the energy of the agent increases by a “grass-energy” quantity, - if not, nothing happens.
	to eat-greedy if grass > 0 [set grass grass – 1 set energy energy + grass-energy] end	To eat greedily, the greedy agents: - check if there is grass in that patch: - if so, the height of grass diminishes of 1 and the energy of the agent increases by a “grass-energy” quantity, - if not, nothing happens.
Resources’ renewal rules	to grow-grass ifelse (grass >= low-high-threshold) [if high-growth-chance >= random-float 100 [set grass grass + 1]] [If low-growth-chance >= random-float 100 [set grass grass + 1]] If grass > max-grass-height [set grass max-grass-height] end	To grow grass, each patch: - check the level of grass: - if the level of grass is greater than or equal to the threshold value, - “throws a dice” to see if it is going to grow by 1 (if the random generated number is below the growing chance expressed by the high-growth-chance parameter), - if the level of grass is lower than the threshold value, - “throws a dice” to see if it is going to grow by 1 (if the random generated number is below the growing chance expressed by the low-growth-chance parameter; with the low-growth-chance being lower than the high-growth chance), - if the level of grass is greater than the maximum value, - assign to grass the “max-grass-height” value.

- Depending on the values of the parameters, the system can have different evolutions. With default parameters, the cooperative population expands first but, in the end, the greedy cows win, as it is shown in Figure 10.

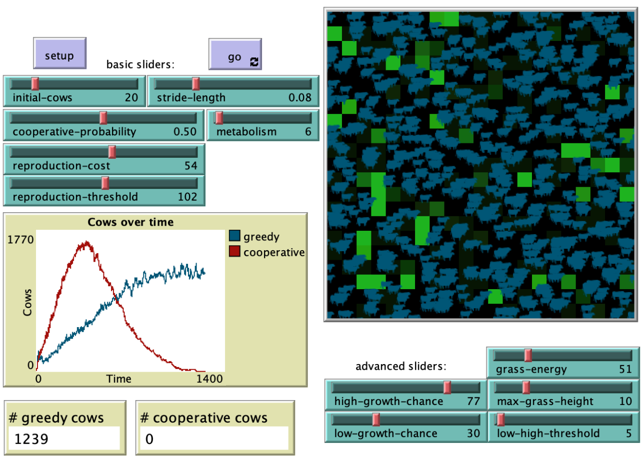


Figure 10. Time evolution of the number of cooperative (in red) and greedy (in blue) agents of the NetLogo “Cooperation” simulation with default parameters (Wilensky, 1997b).

- Changing how much the cows can move at each step (decreasing or increasing the stride-length parameter) determines the number of iterations needed for the greedy population to overcome the cooperative cows. The further the cows can go at each step, the faster the greedy cows will win. Indeed, they will always find grass to eat, even if they have already eaten what was in their previous position. On the opposite, being allowed to move only of short space steps makes the cooperative behavior more convenient, since the resources as "respected" and grass has been given the time and space to grow faster (without eating under the threshold value). The comparison of three graphs obtained with different values of the stride-length parameter is shown in Figure 11. Increasing this parameter, we see that diminishes the time at which happens the surpassing of cooperative cows by the greedy ones.

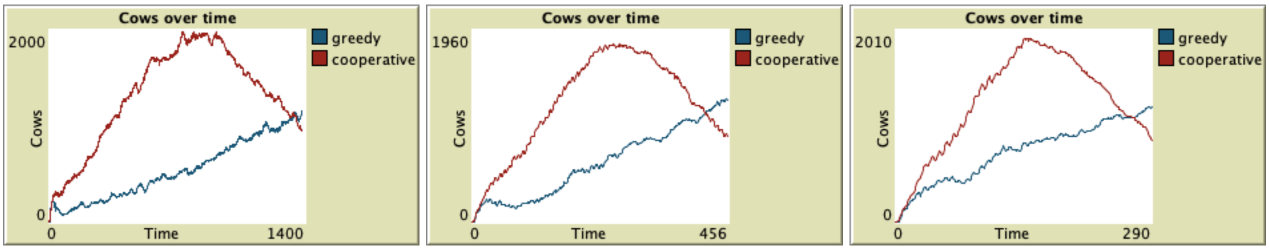


Figure 11. Time evolution of the number of cooperative and greedy agents of the NetLogo "Cooperation" simulation (Wilensky, 1997b) for different values of the stride-length parameter (quantifying how much the cows can move at each step). From left to right, stride-length = 0.5, 0.8 (default), 0.11.

- Another parameter that it is possible to change is the metabolism, which it the amount of energy that each agent spends to move. With little energy spent at every movement, the greedy cows easily overcome the cooperative ones, for similar reasons to those discussed before. If instead we increase the value of the parameter, we arrive at a condition of dynamic equilibrium in which the two populations coexist. Graphs are reported in Figure 12.

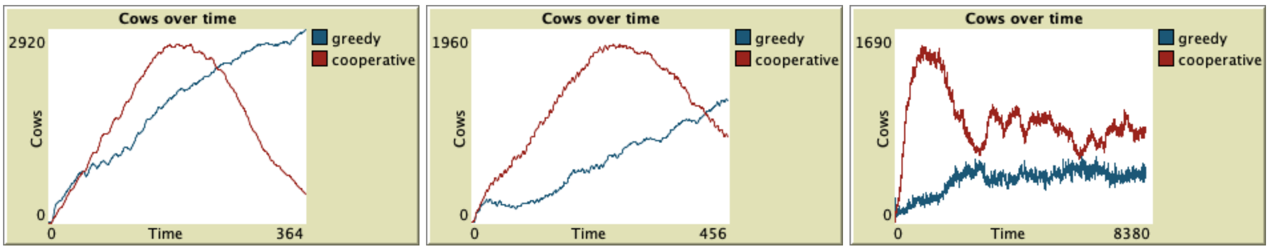


Figure 12. Time evolution of the number of cooperative and greedy agents of the NetLogo "Cooperation" simulation (Wilensky, 1997b) for different values of the metabolism parameter (quantifying the energy that the agents loses at each step). From left to right, metabolism = 3, 6 (default), 11.

- When we experiment with the probability of grass regeneration, we notice that the higher are the growth chance, the faster the greedy population overcomes the cooperative. Indeed, since the greedy cows eat regardless of the amount of resources available, the grass increasing their chance to grow makes easier for the greedy to be successful in their behavior. The opposite happens diminishing the probability of growing which temporarily favors the cooperative strategy. Graphical results are reported in Figure 13.

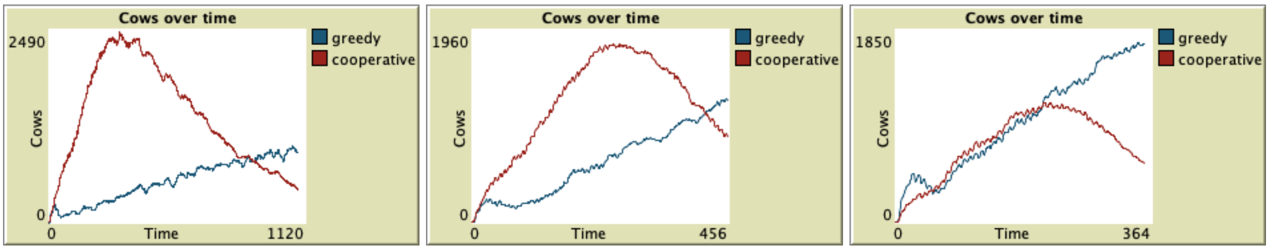


Figure 13. Time evolution of the number of cooperative and greedy agents of the NetLogo "Cooperation" simulation (Wilensky, 1997b) for different values of the low-growth-chance parameter (quantifying the probability that grass grows if its current height is below a given threshold). From left to right, low-growth-chance = 20, 30 (default), 40.

From an epistemological point of view, the articulation of the presentation of the cooperative model and its simulation allowed to point out that:

- the agent-based approach can be useful to model different cooperative (or non-cooperative) evolutionary strategies;
- the simulation allows to perform many different experiments changing the values of the parameters and obtaining in this way different scenarios at a macroscopic level.

During the presentation of the cooperation model, the students were asked two answer two questions on a shared Google Jamboard. The first was asked after the introduction of the basic rules of the cooperation model and required the students to think at the possible evolutions of a system with agents following these rules: *What do we expect from a system where there are only selfish and cooperative agents? What can happen?.* The second question was aimed at making students experiment with the different parameters of the NetLogo Cooperation simulation and try to explain the observed results: *Try some configurations for the "Cooperation" simulation, modifying one parameter at a time: what do you get? Why?.*

The third lesson of the module was concluded with some final remarks on the models addressed. In particular, the predator-prey, voter and cooperation models allow to experience first-hand different forms of modelling that are typical of different disciplines:

- the *mathematical* models that consists of differential equations like those at the basis of the Lotka-Volterra model;
- the *physically-inspired* models that are constructed on models of physical interactions at the microscopic level, like the case of the voter model;
- the *computational* models that are needed in the passage from the analytical or qualitative descriptions of the models to the implementation in a simulation.

These three elements at the basis of the simulations combine to produce not one but many different configurations: the *scenarios*.

4.4. Activity of analogies' development: "From models of systems to real problems"

During the fourth lesson of the course was carried out an activity designed and implemented in collaboration with Elisa Fabbri, a student of the Physics bachelor of the University of Bologna. Elisa Fabbri, under our supervision, wrote her thesis on this activity, from the design phase, to the implementation, to the preliminary data analysis (Fabbri, 2021). That is why this section extensively cites her thesis. The results of the data analysis related to this lesson of the module are the object of Part study 1.

The activity was inspired by the theory of coordination classes (diSessa & Sherin, 1998) and in particular by the idea of span and alignment as characterized in the physics education context by Levrini and diSessa (2008). Indeed, in the process of construction of a coordination class, the theory envisions two typical difficulties that students can display. Both are related to the ability of navigating a multiplicity of contexts in which a specific concept can be identified. These difficulties are:

- the problem of *span,* regarding the ability of using a concept in different contexts in which it is applicable;
- the problem of *alignment*, regarding the ability of reading the same information in a variety of different contexts.

The structure, the philosophy at the basis of the coordination class theory and the specific ideas of span and alignment inspired the design of the activity with the aim of guiding them to experience span and alignment processes that contribute to the construction of the coordination class for the mechanisms underlying the simulations of complex systems. More specifically, we referred to the three agent-based simulations illustrated during the third lesson of the course and discussed in the previous paragraph: the wolves-sheep predation, voting and cooperation simulations. In particular, the activity aimed to lead students extending the concept at the basis of the three agent-based simulations to different real-world contexts and problems and, in turn, to recognize in these the characteristics that made them modellable through such simulations. We underline that the coordination class theory was not used in our case to construct lenses for data analysis nor to investigate specific processes of conceptual change: we only refer to it as an inspiration that allowed us to identify specific foci for the activity.

Concretely, the activity, to be carried out at the end of an explanation on the three simulations, is structured in four phases, explained in detail below.

The first phase has the purpose of verifying to what extent the students are able, at the end of the presentation of the third lesson, to autonomously extend the concepts at the basis of the predator-prey, voting and cooperation simulations to other contexts. They were are asked to answer, through a shared Google Jamboard, the following question: *What real problems do you think you can tackle with each of these simulations?.*

After the initial brain-storming activity, the second phase of the activity consists in a presentation to students of three real-life problems or situations that can be modeled through the agent-based simulations considered. After a brief introduction to the problem, students are asked to “work by analogy” and to fill individually three questionnaires (submitted through Google Form and reported in the Appendix D). In these questionnaires, the agents, mechanisms, and main parameters of each NetLogo simulation were reported, and the students had to associate to each of them the corresponding element in the real-world domain specified. In the following, we discuss the three problems selected and proposed to the students, as well as the *a priori* correspondences that we established between the simulation and the real problem. For each problem presented, students are also asked the question: *Do you think it reasonable to represent these problems through the three corresponding agent simulations? Do you notice any other similarities or differences between real problem and simulation, in addition to those highlighted by the questionnaire?.*

3.4.1. The disappearance of small businesses in favor of large companies (Wolves-sheep predation)

For the wolves-sheep predation simulation (Wilensky, 1997a), in its version which includes the limit for the amount of resources (sheep-wolves-grass version), we have chosen the problem of the disappearance of small businesses in favor of the emergence of large companies, multinationals and online giants. We have, in fact, recognized in this problem an interaction mechanism that can be modeled through the considered simulation. In particular, we recognized in the agents of the simulation, i.e. the “wolf” and “sheep”, the large companies and small businesses respectively. We interpreted the “predation mechanism” as the acquisition of the small businesses by large companies. Similarly, we have assigned to each parameter of the simulation a meaning concerning the real problem, as reported in Table 7.

Table 7. Correspondences between the elements of the wolves-sheep-predation simulation (on the left) and the problem of the disappearance of small businesses in favor of large companies (on the right).

Model and simulation	**Real problem**
Wolf-sheep predation	Disappearance of small businesses in favor of the emergence of large companies, multinationals, and online giants
Wolves	Large companies, multinationals, online giants
Sheep	Small businesses
Mechanism of predation	Acquisition/assimilation of small businesses by large companies
Grass	Clients of the small business
Initial-number-sheep Initial-number-wolves	Initial number of small businesses and large companies in the considered territory (a region, a nation or the internet)
Grass-regrowth-time	Time it takes for customers to need a new product (it changes according to the sector considered and is linked to the frequency with which the product is bought by the buyer)
Sheep-gain-from-food Wolves-gain-from-food	Earnings and the possibility of investing in various kinds of improvements

Sheep-reproduce Wolf-reproduces	Birth of new companies or new locations of the activities considered

3.4.2. The problem of echo chambers (Voting)

As a real-life problem that can be modelled through the voting simulation (Wilensky, 1998), we have chosen the problem of echo chambers. It is a mechanism, particularly evident on social networks, where people tend to communicate only with those who share the same ideas. This ends up amplifying univocal and uncritical visions of an issue because the ideas are strengthened by their repetition within a system. Polarization and separation phenomena occur. We have recognized in this problem an interaction model similar to the one presented in the voting simulation, as each individual is not influenced by the totality of the system (in the problem, all the people registered in the social network), but only by neighboring agents (in the problem, the people with whom you communicate or the groups in which information is exchanged). The correspondence between the parameters and the types of agents of the simulation and the elements of the real problem are shown in the Table 8.

Table 8. Correspondences between the elements of the voting simulation (on the left) and the problem of the formation of echo chambers (on the right).

Model and simulation	**Real problem**
Voting	Constitutions of echo chambers on social networks
Green agents Blue agents	People with different opinions
Neighbors	Friends, relatives, family members, people with whom each agent communicates or exchange information within a social network (for example, people of the same Facebook group)
Color of the agents	Opinion
Change-vote-if-tied? Award-close-to-loser?	Introduction of information from other sources, or acquired outside the echo chamber
Final configuration	Creation of clusters of individuals who share the same opinion zones, and creation of echo chambers

3.4.3. The problem of ecological choices in a city (Cooperation)

As a problem that can be addressed with the cooperation simulation (Wilensky, 1997b), we have chosen a problem related to the ecological and environmental issue. In particular, we contextualized it in a city where some individuals make choices of an ecological nature, such as, for example, the use of public transport or bicycles, and others who instead opt for choices that are unconcerned with respect to the problem, such as for example the exclusive use of cars. Taking this problem into consideration, we recognized the same dynamic of interaction that distinguishes the cooperation simulation, in which each agent interacts with the system which in turn affects how the agents can behave, also determining the success of the cooperative or greedy strategy. The correspondence we identified between the simulation and the problem is reported in Table 9.

Table 9. Correspondences between the elements of the cooperation simulation (on the left) and the problem of ecological choices in a city (on the right).

Model and simulation	**Real problem**
Cooperation	Ecological choices in a city
Greedy cows	People who are careless about making ecological choices, e.g. they do not buy an electric car, always prefer the use of the car to that of the bicycle or public transport
Cooperative cows	People who opt for an ecological lifestyle, e.g. they buy an electric car, use public transport or bicycles
Grass	Renewable resources of various kinds, or even air in a city which can have higher or lower rates of pollution
Grass' consumption	Consumption of renewable resources or deterioration of the environment, e.g. air pollution in a city)
Strategy of grass' consumption by greedy cows	Modality of resource consumption based exclusively on individual well-being and characterized by choices dictated by comfort or convenience
Strategy of grass' consumption by cooperative cows	Far-sighted modality of resource consumption based on collective well-being
Reproduction-cost	Resource consumption necessary for individual well-being
Grass-energy	Advantage taken using the environmental resources
Threshold for grass' growth	Level under which which human consumption has an impact that does not affect the system itself, e.g. a certain rate of environmental pollution in a city

After the students completed the three questionnaires, began the third phase of the activity in which the participants were asked to answer again the question of phase 1 of the activity, adding to the initial Google Jamboard other problems that can be represented by the three simulations. This phase aims to verify the effectiveness of the activity proposed in the second phase in helping students to extend the main concepts at the basis of the three simulations to other application contexts.

Finally, the last phase of the activity consists in a guided collective discussion with the students. In particular, students are asked the following questions: *What do the problems described by a specific simulation (wolves-sheep predation, voting or cooperation) have in common? What distinguishes them from those that can be represented with the other simulations? What are the interaction mechanics embedded in the problems identified?.* While the brainstorming activity on the types of problems proposed in phases 1 and 3 was aimed at creating the conditions for the enrichment of the span, these concluding questions aim to make students think about the problem of alignment. Indeed, they are asked to trace, within different application contexts, a common concept, idea or piece of information.

4.5. Group activity of construction of scenarios based on simulations

The fifth day of the laboratory, to the students was proposed a future-oriented activity that guided them to work with agent-based simulation with the goal of constructing possible, probable, and desirable scenarios for real-world problems of their interest. The activity was extensively based on the recent literature in future-oriented science education (Branchetti et al., 2019, Levrini et al., 2019, Levrini et al., 2021) and on the results of the I SEE (www.iseeproject.eu) and FEDORA (www.fedora-project.eu) European projects, coordinated by the University of Bologna and in which we have been personally involved. In turn, these projects borrow many concepts from the literature in the interdisciplinary field of Futures Studies which involves sociologists, philosophers, as well as STEM, economics, politics, and entrepreneurship professionals. The Futures Studies approach draws upon the science of complex systems and, consistently, questions the common belief that futures are only matters of making predictions from the present towards, instead stressing futures as ways to open a range of possibilities, whose evolution follows (in the medium and long term) the non-linear dynamics of complex systems. Since accurate predictions are not necessary nor possible (due to scientific constraints), it is socially, economically, and personally important to develop skills for thinking about possibilities and ways to realize possible futures rather than predicting exactly what will happen. In this possibility perspective, the existence of a plurality of futures is crucial and the keyword is, again, scenario. Within this perspective, different kinds of futures have been introduced: possible, plausible, probable, and preferable. The relationship between them is often represented with a "futures cone" (Hancock & Bezold, 1994), elaborated by Voros (2003). In Figure 14 we report the graphic elaboration of the Voros' cone developed in the I SEE project.

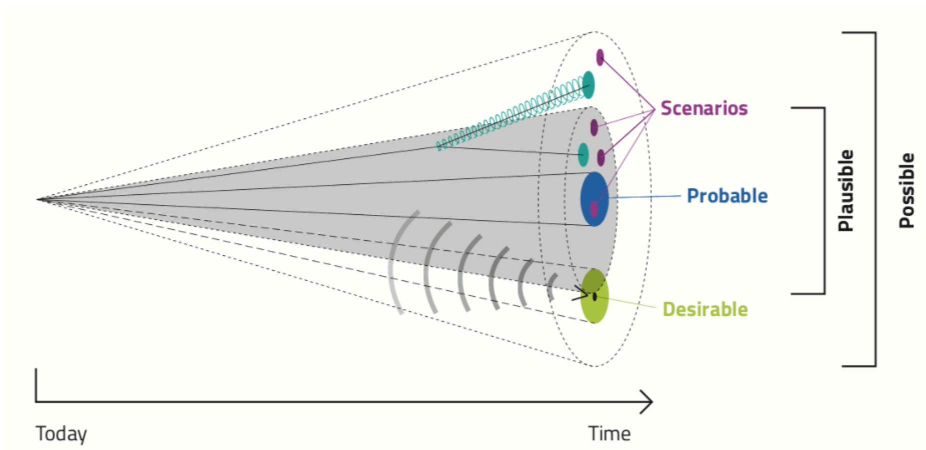


Figure 14. The futures cone of the Erasmus+ project I SEE "Inclusive STEM Education to Enhance the capacity to aspire and to imagine future careers", re-elaborated from (Voros, 2003).

In the cone we see that the largest range corresponds to all *possible* futures, including all the futures we can imagine – also what might happen, even if unlikely. In the cone, possible futures correspond to the largest range. The *plausible* futures concern cases that could happen according to our current knowledge of how things work in the present. The class of plausible futures contains a sub-class of cases that are supposed likely to happen as a continuance of current trends: these are named *probable* futures. While plausible and probable futures are largely concerned with informational or cognitive knowledge, preferable (also known as *desirable*) scenarios can depend, with high sensitivity, on contingencies or unexpected choices. Such contingencies and choices can concern what people want to happen; in other words, these futures are more emotional rather than cognitive and are thus more subjective than the other versions. In figure are also represented the scenarios which are “pictures of the future” and can be possible, plausible, probable, or desirable. The wavefront in the bottom part of the image represents the procedure of back-casting which is a way to imagine the future starting from the future itself and proceeding backward to identify the possible actions that through history can lead to the present situation. The turquoise circles at the top of the cone represent two different scenarios that result from a bifurcation point and from feedback-amplification processes.

Before presenting the group activity, we introduced the connections that exist between simulations and the future. Using the answers that the students gave during the ice-breaking activity of the second lesson, we underlined the reasons for which it can be important to reflect on the future in a laboratory on simulations of complex systems. The first reason is related to the crucial phase of life in which the participants are supposed to be: indeed, being for the students a context for university orientation, the laboratory should give them the possibility to reflect on their own future and on their career. The second reason is connected to the profound relationship that exists between science and future: future is intrinsic to science and physics, in particular, was born also to predict future events and manage the fear of the unknown. The third reason is even more specific and regards scientific simulations, the main topic of the course. As seen in the fourth lesson, these tools can teach us a way to analyze real problems, to obtain scenarios and, hence, make us think about what *could* happen in the future, instead of what *will* happen. Because of their experimental character, simulations can play the role of laboratories to prepare to the future.

Then, the future’s cone was introduced as a way to summarize the types of future that the discipline of futures study envisions, and the concept of scenario, illustrating examples from the Global Environment Outlook (UNEP, 2002, 328 ff).

The students were then divided in the groups in which they had already worked in the ice-breaking activity and were asked to carry out a future-oriented activity structured in different tasks. The first task consists in the identification of a real-world problem of students’ interest, followed by the request to explore possible future scenarios on the basis of NetLogo agent-based simulations. Then students are asked to imagine a desirable scenario and to engage in a back-casting procedure, identifying actions, decisions, policies, contingencies which have made it possible to realize the ideal future in 2040. To exploit the role of individual agency in the imagination of the future, in the fourth phase students are required to make explicit which role they have in the path of changes from the present to the future they foresee, as professionals, members of society, and as individual in general. In the end, the students are asked to prepare a presentation about their story of success as a way to summarize the work in the activity. In Table 10, we report the specific questions proposed to the students. These questions were illustrated before the beginning of the work in groups and also reported in a work sheet that the students could refer to. The decision to use of the work sheet to collect the written – even if necessarily summarized – answers of the groups was triggered by the result of a preliminary study carried out with university students in December 2020 (Barelli & Levrini, 2021a), in which an analogous activity was implemented. In that case, for the students were very difficult to keep the pace of the activity with all the tasks. Hence, we thought to design this a tool to support them in carrying out their analysis. The extended version of the questionnaire is reported in Appendix E.

Table 10. Tasks of the future-oriented activity.

Task 1 - Identify the problem	
Pick a problem that you feel urgent today and you would like it resolved in 2040. The problem can concern any context: your schools, your city, Italy, Europe, or the whole world. Each member of the group proposes a problem of their interest. Discuss everyone's proposals, then vote for the most convincing one. At the end of the discussion, write the problem you have identified, explaining the context you are referring to.	30 mins
Task 2 - Explore different possible futures	
Inspiring yourself with the simulation you think is most suitable, explore possible evolutions of the problem from the present to the future and imagine what scenarios you could arrive at in 2040. Briefly describe at least three alternative future situations that the simulation inspired you.	30 mins
Task 3 - Imagine a desirable scenario for 2040	
Now imagine that in 2040 the problem you selected has been solved. Describe in as much detail as possible your desirable scenario for 2040. Include in your description the stakeholders, the interests at stake, how people live in the context in which you are located, the elements of novelty and those of continuity with respect to the past. At this stage... dream! Throw your imagination beyond the obstacles of the present! As you enrich your scenario, describe it here, along with its features.	60 mins
Task 4 - Back-casting and action planning	
Starting from the desirable scenario, think about what actions, decisions, policies, contingencies made it possible to realize the ideal future in 2040. Were there any bifurcations, moments of uncertainty? What role have the stakeholders played? Use this space to write down the most significant passages of the timeline.	90 mins
Task 5 - Tell the story of success	
Prepare a 10-minute presentation to do during the last meeting to tell everyone your success story of which you were the agents, the protagonists. To do this, decide on a name for your group with which to introduce yourself to others, give yourself a role in the story and develop a presentation method (a story, slides, a video ...). In the presentation, highlight the role that simulation has played for you in analyzing the problem, imagining the scenarios and creating your success story.	120 mins

4.6. Groups' presentations and conclusion

In the final lesson of the course, the groups presented to all participants their work on the future-oriented activity with 10-minutes presentations. In the end, time was left for final remarks and discussion, and the students filled the standardized evaluation questionnaire from the orientation unit of the University of Bologna. This questionnaire is reported in the Appendix F.

4.7. Final individual interviews

At the end of the course, the students were asked to participate to an extra voluntary individual session to reflect on the contents of the course and provide suggestions for future editions. The students were contacted by e-mail as follows:

> *Given your active participation in the course, I would like to be able to have a final chat with you, to pull the strings of the course and ask you how you lived the experience, what were its strengths or the most difficult aspects, so that to improve the lessons and their articulation in view of the next editions. It will be an individual chat with me, about 30-45 minutes, on the Teams platform. It is nothing for which you have to "prepare" first: it is just a way to understand what you remember of the course, what to enhance and what to improve. In addition, it will be an opportunity for you to ask questions both on the university course in general or on the specific contents of the course.*

Eight students positively answered to the call and agreed to be interviewed. The interviews took place between two and three weeks after the end of the course. To conduct the interview, we used a semi-structured protocol articulated in four different sections. The questions of each section are reported in Table 11.

In the first section, the students were asked to recall the main things they had learnt during the course about simulations as scientific tools and to focus, in particular on the agent-based approach to modelling and simulation. A question was aimed at understanding if they recognized a novelty in the agent-based simulation approach with respect to other models encountered at school.

The second section was the most articulated one, because the students were progressively guided to construct their agent-based model for the phenomenon of virus spreading. Indeed, even if this example was not addressed during the course, it was chosen for its tragic connection with the current pandemic times and because it is often taken as an example to reflect on the interaction mechanisms in an agent-based, decentralized perspective. We recall for example the work by Barth-Cohen who proposed to her students different problem contexts that exhibit complex systems behaviors that can be construed through decentralized causality. One of these problems is the spread of a virus, in which the phenomena at a macroscopic level (the time evolution of the number of susceptible, infected, and recovered individuals) are determined by the interactions of the subparts, individuals (the interactions between agents of different epidemiological statuses) at the microscopic level (Barth-Cohen, 2012, p. 51-52). The first questions we asked to the students were exploratory (*What can it mean to model a virus spreading phenomenon? What comes to your mind?*): we did not want to implicitly suggest the idea of referring to the agent-based modelling strategy and that is why we did not mention terms like “rule”, “population”, “individual” or “agents”, nor we did refer to the idea of “simulation” but only to “model”. Then, the questions become more focused when we ask the students to design a simulation to model the spread of a virus. Here, we make the students focus on the agent-based approach to modelling and on the rules which characterize it (*What would you do? What rules would you choose to model this phenomenon?*). The last questions require the students to move even further, trying to recognize analogies between the three simulations explored in the course (the predator-prey, the voter, and the cooperation ones) and this problem of the virus’ spreading (*Do you see any possible links between these models and the issue of virus spreading? If so, which ones? If not, why?*). The students had already experienced a similar way to reason on the problems during the fourth lesson of the course, but while in the previous case they had been given a different real-world context for each model, here they have only one phenomenon to connect to three models and simulations. To help them focusing the level of the analogy, we asked at which level(s) they recognized the similarity between the virus' spreading and the three simulations (*If you identified any similarity, at what level were they? Does it concern a similarity of global, overall phenomena, or of mechanisms of interaction between agents, or other?*). With these final questions, we wanted to check whether the interaction models we introduced had become for the students a way to reinterpret the modelling they had reached on the spreading phenomenon.

The third phase of the protocol was aimed at making the students reflect on the knowledge and competences they had put into play during the course and, in particular, what kind of knowledge learnt at school they perceived as more useful in the course and, in turn, which competences learnt in the course they can be bring to their school contexts.

A final section was left for further comments, remarks, and questions by the students.

Table 11. Semi-structured protocol for the final individual interviews.

Section A: The role of simulation in the sciences
The central theme of the course was simulations. - What did you understand about simulation as a scientific tool? - How and why are they used? - What models are there behind the simulations?
During the course we explored in detail a particular type of simulations, which are the agent-based ones. - What did you understand about this approach to the modeling of phenomena? - Do you recognize a novelty in this type of modeling compared to the models you have encountered at school in physics, mathematics, science? If so, how would you describe this novelty?
Section B: Modelling the issue of virus spreading
A topic that we did not explicitly address during the course, but which is closely related to what we have seen is the use of simulations to model the spread of a virus. - Is it something you have already reasoned about, perhaps even inspired by the course, or at school, or is this the first time? - What can it mean to model a virus spreading phenomenon? What comes to your mind?
Imagine that you have to design a simulation for this purpose. - What would you do? - What rules would you choose to model this phenomenon?
Look back at the three models we explored in more details during the course (the predator-prey, the voter, and the cooperation models). - Do you see any possible links between these models and the issue of virus spreading? If so, which ones? If not, why? - If you identified any similarity, at what level were they? Does it concern a similarity of global, overall phenomena, or of mechanisms of interaction between agents, or other?
Section C: The knowledge and competences put into play during the course
The course included many different activities, from lectures, to group-works, to tasks to do individually. - To carry out the activities, did you feel to be using knowledge that was provided to you by the school and school subjects? - In what activities did you feel that the school knowledge you had served you most to get into the topic that was being addressed? - What knowledge were you useful for following the activity on the three agent-based simulations, the activity of imagining or interpreting problems and the activity of constructing scenarios?

- In general, have you noticed something different in the way of thinking about models, problems, scenarios, simulations, future than what you are used to? - Did you notice any particular dynamics during the work in groups, e.g. moments of conflict, resolution strategies, etc.? - What knowledge or skills do you think you have learned from this workshop and that you can use at school, with your classmates and with your teachers?
Section D: Final comments
We arrived at the end of our interview: - Do you have other comments with respect to the course, things that intrigued you, about which you want to ask us questions? - Thinking about the students who will attend it next year, would you have any suggestions for us to improve our proposal?

5. Data collection tools

As already reported in the module's description section, several data were collected during the course. We used individual questionnaires, shared digital boards (Google Jamboards), sheet and presentations produced by group-works, collective discussions. Moreover, all the lessons, the group-works and the final interviews were video-recorded. In Table 12 we summarize, for each lecture, which data collection tools were used and a summary of the content.

Table 12. Summary of the data collection tools used in the different lessons of the course.

Lesson	Data collection tool	Content of the tool
Lesson 1	/	/
Lesson 2	Shared boards for the ice-breaking activity (7 boards, one per group)	*For each of the "red threads" of the module (interdisciplinarity, future, science-society intertwining), write:* - *Why you are interested in the issue* - *Why simulations are related with the issue*
	Videorecording of the students' presentations of the students and discussion	Each group had 2 minutes to communicate to the big group the most important idea they had discussed.
Lesson 3	Shared collective board for triggering inquiry and explanation with the three simulations	Specific questions to make student participate i) in the modelling process behind the formulation of the three agent based simulations, ii) in the explanation of emergent phenomena, iii) in the practice of experimentation with the NetLogo simulations. For details, see Section 3.3.
Lesson 4	Shared collective board for brainstorming on problems addressable on the basis of the three simulations (2 boards, one before and one after the work on analogies)	*What real problems do you think you can tackle through each of these simulations?*
	Individual questionnaires for the construction of analogies between NetLogo simulations and real-life problems	For each of the given problems, identify the correspondence between the elements of the reference simulation (agents, features of the agents, mechanisms of interaction, global behavior) and the elements of the real-world problem. For details, see Appendix D.

	Videorecording of the final discussion	*What do the problems described by a specific simulation (wolves-sheep predation, voting or cooperation) have in common? What distinguishes them from those that can be represented with the other simulations? What are the interaction mechanics embedded in the problems identified?*
Lesson 5	Shared work sheets for guiding the future-oriented activity (7 sheets, one per group)	Tasks: identify a problem of interest, explore different possible futures, imagine a desirable scenario for 2040, develop a back-casting and action planning, tell the story of success. For details see Appendix E.
Lesson 6	Videorecording of the groups' presentations	Presentation of the work done in groups over the future-oriented activity.
	Videorecording of the final discussion	Final remarks of the instructors and comments by the students on the future-oriented activity.
	Standardized university questionnaire	Rate of the orientation activity. See Appendix F.
Interviews	Semi-structured interview protocol	Sections of the protocol: recall the role of simulations in the sciences, model the phenomenon of virus spreading, reflect on the knowledge and competences put into play during the course. For details see Section 3.7.
	Videorecording of the individual interviews (8, one per student)	Students' answers to the interview protocol.

6. Module's implementation

The module was implemented in 6 lessons of three hours each between mid-January and the end of February 2021. All lessons took place in the afternoon, after school time. As already explained, the laboratory was part of the initiatives organized by the Department of Physics and Astronomy within the PLS university orientation program (http://www.pls.unibo.it/it). More than 50 students sent their request to participate in the Laboratory on Simulations of complex systems and 35 of them were selected. The criteria of selection were the same of the PLS laboratories, i.e. avoid the presence of more than 5 students from the same class and, guarantee the gender balance as more as possible.

All students attended the third or fourth year of a dozen of secondary schools in Emilia Romagna. The majority (30 out of 35) attended a "scientific lyceum", which is a type of high school centered on scientific subjects; 3 students came from a "classical lyceum", which is focused on teaching-learning humanities and ancient languages; 2 students attended a technical-aeronautic institute.

Before the selection phase, there was a dramatic majority of males interested in attending the laboratory. As a result of the selection, 25 males and 10 females were admitted at the course.

During the course, several group activities were carried out. Seven groups of five students each were arranged in advance following similar criteria to those of the previous selection, i.e. avoid as much as possible the presence of more students of the same class in the same group, and guarantee the presence of at least one female student in each group.

To ensure the anonymity of the students, in this chapter we will refer to the students using identification codes. They are numbered between 1 and 35 and the number is preceded by the gender identifier (M for males and F for females). The order of the numbers corresponds to the identifier of the groups: the first group have students from 1 to 5, the second from 6 to 10, the third from 11 to 15, and so on.

The students took part at most of the activities of the course. Only one participant (M11) attended only one lesson. 8 students (M5, M6, M7, M22, M23, M24, M28, F34) missed one lecture only. 1 student (F10) missed two of them.

In Table 13 we report the students' identifiers, the group in which they worked and the presence at each of the six lessons of the course. In the last column are indicated the students who took part at the final individual interviews. For the eight students who took part in the final interviews, we also created a pseudonym that made easier to refer to them in the presentation of results.

Table 13. Summary of the students' identifiers and division in groups during the course and their participation in the activities of the module.

	Student identifier	Pseudonym	Lesson 1	Lesson 2	Lesson 3	Lesson 4	Lesson 5	Lesson 6	Interview
Group 1	M1		x	x	x	x	x	x	
	F2		x	x	x	x	x	x	
	M3		x	x	x	x	x	x	
	M4	Davide	x	x	x	x	x	x	x
	M5		x	x	x	x	x	ABSENT	
Group 2	M6	Giacomo	x	x	ABSENT	x	x	x	x
	M7		x	ABSENT	x	x	x	x	
	M8		x	x	x	x	x	x	
	M9		x	x	x	x	x	x	
	F10	Emilia	x	x	x	x	ABSENT	ABSENT	x
Group 3	M11		ABSENT	x	ABSENT	ABSENT	ABSENT	ABSENT	
	M12		x	x	x	x	x	x	
	M13		x	x	x	x	x	x	
	F14	Elisa	x	x	x	x	x	x	x
	F15	Valeria	x	x	x	x	x	x	x
Group 4	M16	Alessio	x	x	x	x	x	x	x
	F17	Federica	x	x	x	x	x	x	x
	M18		x	x	x	x	x	x	
	M19	Jonathan	x	x	x	x	x	x	x
	M20		x	x	x	x	x	x	
Group 5	F21		x	x	x	x	x	x	
	M22		x	x	ABSENT	x	x	x	
	M23		x	x	ABSENT	x	x	x	
	M24		x	x	x	x	ABSENT	x	
	M25		x	x	x	x	x	x	

Group 6	F26		x	x	x	x	x	x	
	M27		x	x	x	x	x	x	
	M28		x	x	x	x	ABSENT	x	
	M29		x	x	x	x	x	x	
	M30		x	x	x	x	x	x	
Group 7	F31		x	x	x	x	x	x	
	M32		x	x	x	x	x	x	
	M33		x	x	x	x	x	x	
	F34		x	x	ABSENT	x	x	x	
	M35		x	x	x	x	x	x	

7. Research Questions

Based on the research cited in the background (Section 3), this chapter addresses the following research questions:

- RQ1. How did the students put into play future-scaffolding skills during the future-oriented activity?
- RQ2. How did the students describe the future-scaffolding skills developed?
- RQ3. How the future-scaffolding skills can be operationalized in the context of a future-oriented activity about the analysis of a complex topic through agent-based simulations?

8. Methodology of data analysis

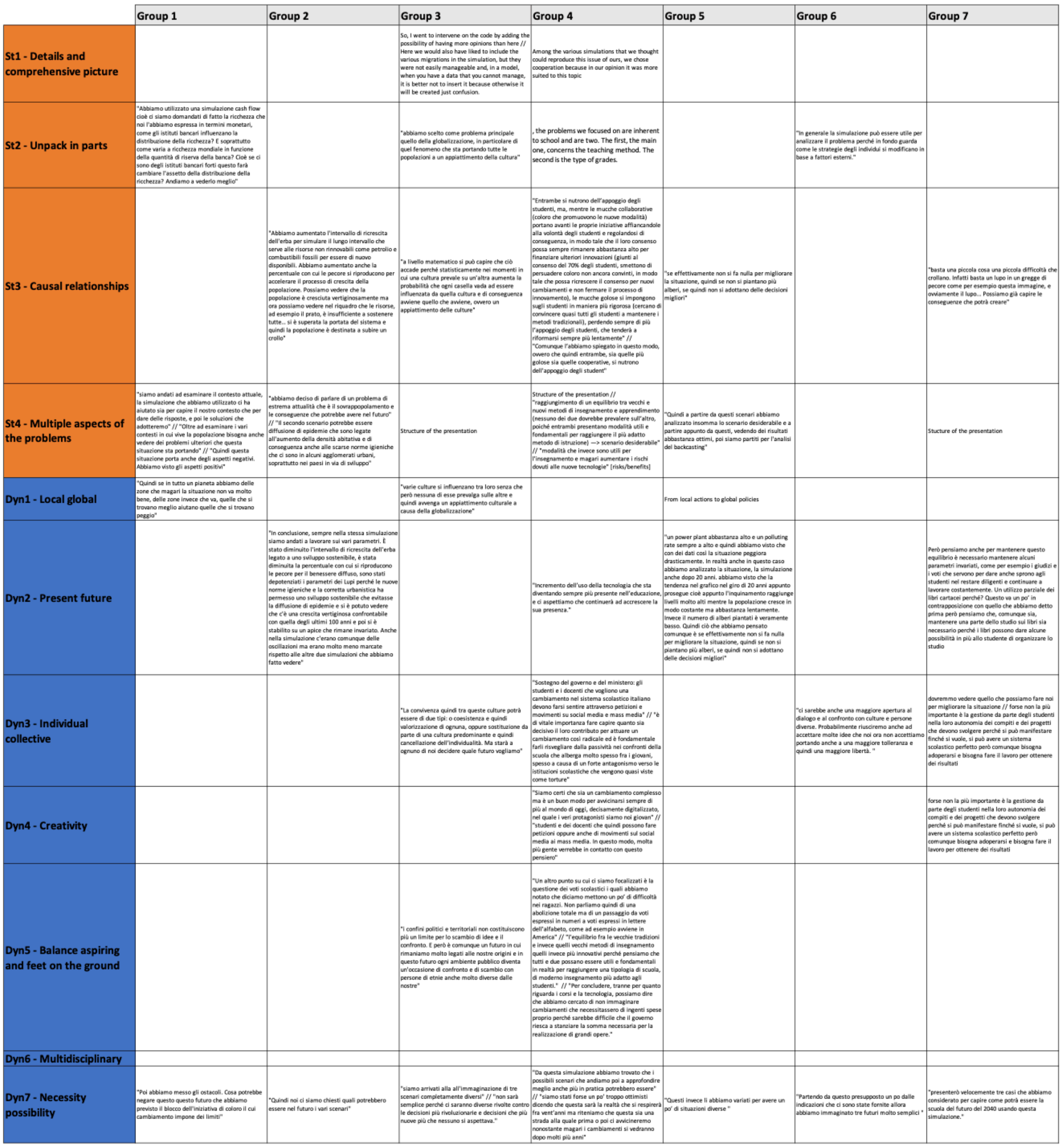
The data analysis was articulated in the following phases:

8.1. Data organization, data reduction and top-down analysis of the groups' presentations

In this first phase, the data sources were the video-recordings of students' final presentations at the end of the future-oriented activity. They were transcribed and anonymized using pseudonyms in which the only reference kept is to students' gender. Being the presentations video recorded, we added to the transcript the slides that the students used for their presentation, and, in the case of group 4, we also considered the text they wrote as captions of the Instagram posts they used as a presentation.

The analysis has been conducted in a top-down way even if the possibility of further bottom-up evidence was always kept open. We analyzed the seven final presentations of the students to identify signals that could indicate the development by the students of structural and dynamical future-scaffolding skills. Differently than in previous studies (Levrini et al., 2019; Levrini et al., 2021), in this experience we did not directly ask the students if and how their perception of the future changed throughout the module nor what competences they felt to have put into play during the future-oriented activity. On the opposite, we looked at their presentations as the results of the students' understanding of the topic, hence of their knowledge and their competences.

Methodologically, we followed a similar procedure to that of the paper by Levrini and colleagues (2021) where the researchers checked the students' claims about the skills developed against the outputs of their work in groups, with respect to which the future-scaffolding skills were detected as "put into action". In the analysis of the final presentations, we considered the put into action of the skills as an achievement of the group as a whole, without distinguishing between the students that said the specific sentences. Also this methodological choice is grounded in the last study on future-scaffolding skills by Levrini and colleagues (2021).



	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
St1 - Details and comprehensive picture			So, I went to intervene on the code by adding the possibility of having more opinions than here // Here we would also have liked to include the various migrations in the simulation, but they were not easily manageable and, in a model, when you have a data that you cannot manage, it is better not to insert it because otherwise it will be created just confusion.	Among the various simulations that we thought could reproduce this issue of ours, we chose cooperation because in our opinion it was more suited to this topic			
St2 - Unpack in parts	"Abbiamo utilizzato una simulazione cash flow cioè ci siamo domandati di fatto la ricchezza che noi l'abbiamo espressa in termini monetari, come gli istituti bancari influenzano la distribuzione della ricchezza? E soprattutto come varia a ricchezza mondiale in funzione della quantità di riserva della banca? Cioè se ci sono degli istituti bancari forti questo farà cambiare l'assetto della distribuzione della ricchezza? Andiamo a vederlo meglio"		"abbiamo scelto come problema principale quello della globalizzazione, in particolare di quel fenomeno che sta portando tutte le popolazioni a un appiattimento della cultura"	, the problems we focused on are inherent to school and are two. The first, the main one, concerns the teaching method. The second is the type of grades.		"In generale la simulazione può essere utile per analizzare il problema perché in fondo guarda come le strategie degli individui si modificano in base a fattori esterni."	
St3 - Causal relationships		"Abbiamo aumentato l'intervallo di ricrescita dell'erba per simulare il lungo intervallo che serve alle risorse non rinnovabili come petrolio e combustibili fossili per essere di nuovo disponibili. Abbiamo aumentato anche la percentuale con cui le pecore si riproducono per accelerare il processo di crescita della popolazione. Possiamo vedere che la popolazione è cresciuta vertiginosamente ma ora possiamo vedere nel riquadro che le risorse, ad esempio il prato, è insufficiente a sostenere tutte... si è superata la portata del sistema e quindi la popolazione è destinata a subire un crollo"	"a livello matematico si può capire che ciò accade perché statisticamente nei momenti in cui una cultura prevale su un'altra aumenta la probabilità che ogni casella vada ad essere influenzata da quella cultura e di conseguenza avviene quello che avviene, ovvero un appiattimento delle culture"	"Entrambe si nutrono dell'appoggio degli studenti, ma, mentre le mucche collaborative (coloro che promuovono le nuove modalità) portano avanti le proprie iniziative affiancandole alla volontà degli studenti e regolandosi di conseguenza, in modo tale che il loro consenso possa sempre rimanere abbastanza alto per finanziare ulteriori innovazioni (giunti al consenso del 70% degli studenti, smettono di persuadere coloro non ancora convinti, in modo tale che possa ricrescere il consenso per nuovi cambiamenti e non fermare il processo di innovamento), le mucche golose si impongono sugli studenti in maniera più rigorosa (cercano di convincere quasi tutti gli studenti a mantenere i metodi tradizionali), perdendo sempre di più l'appoggio degli studenti, che tenderà a riformarsi sempre più lentamente" // "Comunque l'abbiamo spiegato in questo modo, ovvero che quindi entrambe, sia quelle più golose sia quelle cooperative, si nutrono dell'appoggio degli student"	"se effettivamente non si fa nulla per migliorare la situazione, quindi se non si piantano più alberi, se quindi non si adottano delle decisioni migliori"		"basta una piccola cosa una piccola difficoltà che crollano. Infatti basta un lupo in un gregge di pecore come per esempio questa immagine, e ovviamente il lupo... Possiamo già capire le conseguenze che potrà creare"
St4 - Multiple aspects of the problems	"siamo andati ad esaminare il contesto attuale, la simulazione che abbiamo utilizzato ci ha aiutato sia per capire il nostro contesto che per dare delle risposte, e poi le soluzioni che adotteremo" // "Oltre ad esaminare i vari contesti in cui vive la popolazione bisogna anche vedere dei problemi ulteriori che questa situazione sta portando" // "Quindi questa situazione porta anche degli aspetti negativi. Abbiamo visto gli aspetti positivi"	"abbiamo deciso di parlare di un problema di estrema attualità che è il sovrappopolamento e le conseguenze che potrebbe avere nel futuro" // "Il secondo scenario potrebbe essere diffusione di epidemie che sono legate all'aumento della densità abitativa e di conseguenza anche alle scarse norme igieniche che ci sono in alcuni agglomerati urbani, soprattutto nei paesi in via di sviluppo"	Structure of the presentation	Structure of the presentation // "raggiungimento di un equilibrio tra vecchi e nuovi metodi di insegnamento e apprendimento (nessuno dei due dovrebbe prevalere sull'altro, poiché entrambi presentano modalità utili e fondamentali per raggiungere il più adatto metodo di istruzione) —> scenario desiderabile" // "modalità che invece sono utili per l'insegnamento e magari aumentare i rischi dovuti alle nuove tecnologie" [risks/benefits]	"Quindi a partire da questi scenari abbiamo analizzato insomma lo scenario desiderabile e a partire appunto da questi, vedendo dei risultati abbastanza ottimi, poi siamo partiti per l'analisi del backcasting"		Stucture of the presentation
Dyn1 - Local global	"Quindi se in tutto un pianeta abbiamo delle zone che magari la situazione non va molto bene, delle zone invece che va, quelle che si trovano meglio aiutano quelle che si trovano peggio"		"varie culture si influenzano tra loro senza che però nessuna di esse prevalga sulle altre e quindi avvenga un appiattimento culturale a causa della globalizzazione"		From local actions to global policies		
Dyn2 - Present future		"In conclusione, sempre nella stessa simulazione siamo andati a lavorare sui vari parametri. È stato diminuito l'intervallo di ricrescita dell'erba legato a uno sviluppo sostenibile, è stata diminuita la percentuale con cui si riproducono le pecore per il benessere diffuso, sono stati depotenziati i parametri dei Lupi perché le nuove norme igieniche e la corretta urbanistica ha permesso uno sviluppo sostenibile che evitasse la diffusione di epidemie e si è potuto vedere che c'è una crescita vertiginosa confrontabile con quella degli ultimi 100 anni e poi si è stabilito su un apice che rimane invariato. Anche nella simulazione c'erano comunque delle oscillazioni ma erano molto meno marcate rispetto alle altre due simulazioni che abbiamo fatto vedere"		"Incremento dell'uso della tecnologia che sta diventando sempre più presente nell'educazione, e ci aspettiamo che continuerà ad accrescere la sua presenza."	"un power plant abbastanza alto e un polluting rate sempre a alto e quindi abbiamo visto che con dei dati così la situazione peggiora drasticamente. In realtà anche in questo caso abbiamo analizzato la situazione, la simulazione anche dopo 20 anni. abbiamo visto che la tendenza nel grafico nel giro di 20 anni appunto prosegue cioè appunto l'inquinamento raggiunge livelli molto alti mentre la popolazione cresce in modo costante ma abbastanza lentamente. Invece il numero di alberi piantati è veramente basso. Quindi ciò che abbiamo pensato comunque è se effettivamente non si fa nulla per migliorare la situazione, quindi se non si piantano più alberi, se quindi non si adottano delle decisioni migliori"		Però pensiamo anche per mantenere questo equilibrio è necessario mantenere alcuni parametri invariati, come per esempio i giudizi e i voti che servono per dare anche sprono agli studenti nel restare diligenti e continuare a lavorare costantemente. Un utilizzo parziale dei libri cartacei perché? Questo va un po' in contrapposizione con quello che abbiamo detto prima però pensiamo che, comunque sia, mantenere una parte dello studio sui libri sia necessario perché i libri possono dare alcune possibilità in più allo studente di organizzare lo studio
Dyn3 - Individual collective			"La convivenza quindi tra queste culture potrà essere di due tipi: o coesistenza e quindi valorizzazione di ognuna, oppure sostituzione da parte di una cultura predominante e quindi cancellazione dell'individualità. Ma starà a ognuno di noi decidere quale futuro vogliamo"	"Sostegno del governo e del ministero: gli studenti e i docenti che vogliono una cambiamento nel sistema scolastico italiano devono farsi sentire attraverso petizioni e movimenti su social media e mass media" // "è di vitale importanza fare capire quanto sia decisivo il loro contributo per attuare un cambiamento così radicale ed è fondamentale farli risvegliare dalla passività nei confronti della scuola che alberga molto spesso fra i giovani, spesso a causa di un forte antagonismo verso le istituzioni scolastiche che vengono quasi viste come torture"		"ci sarebbe anche una maggiore apertura al dialogo e al confronto con culture e persone diverse. Probabilmente riusciremo anche ad accettare molte idee che noi ora non accettiamo portando anche a una maggiore tolleranza e quindi una maggiore libertà. "	dovremmo vedere quello che possiamo fare noi per migliorare la situazione // forse non la più importante è la gestione da parte degli studenti nella loro autonomia dei compiti e dei progetti che devono svolgere perché si può manifestare finché si vuole, si può avere un sistema scolastico perfetto però comunque bisogna adoperarsi e bisogna fare il lavoro per ottenere dei risultati
Dyn4 - Creativity				"Siamo certi che sia un cambiamento complesso ma è un buon modo per avvicinarsi sempre di più al mondo di oggi, decisamente digitalizzato, nel quale i veri protagonisti siamo noi giovan" // "studenti e dei docenti che quindi possono fare petizioni oppure anche di movimenti sul social media ai mass media. In questo modo, molta più gente verrebbe in contatto con questo pensiero"			forse non la più importante è la gestione da parte degli studenti nella loro autonomia dei compiti e dei progetti che devono svolgere perché si può manifestare finché si vuole, si può avere un sistema scolastico perfetto però comunque bisogna adoperarsi e bisogna fare il lavoro per ottenere dei risultati
Dyn5 - Balance aspiring and feet on the ground			"i confini politici e territoriali non costituiscono più un limite per lo scambio di idee e il confronto. E però è comunque un futuro in cui rimaniamo molto legati alle nostre origini e in questo futuro ogni ambiente pubblico diventa un'occasione di confronto e di scambio con persone di etnie anche molto diverse dalle nostre"	"Un altro punto su cui ci siamo focalizzati è la questione dei voti scolastici i quali abbiamo notato che diciamo mettono un po' di difficoltà nei ragazzi. Non parliamo quindi di una abolizione totale ma di un passaggio da voti espressi in numeri a voti espressi in lettere dell'alfabeto, come ad esempio avviene in America" // "l'equilibrio fra le vecchie tradizioni e invece quelli vecchi metodi di insegnamento quelli invece più innovativi perché pensiamo che tutti e due possano essere utili e fondamentali in realtà per raggiungere una tipologia di scuola, di moderno insegnamento più adatto agli studenti." // "Per concludere, tranne per quanto riguarda i corsi e la tecnologia, possiamo dire che abbiamo cercato di non immaginare cambiamenti che necessitassero di ingenti spese proprio perché sarebbe difficile che il governo riesca a stanziare la somma necessaria per la realizzazione di grandi opere."			
Dyn6 - Multidisciplinary							
Dyn7 - Necessity possibility	"Poi abbiamo messo gli ostacoli. Cosa potrebbe negare questo questo futuro che abbiamo previsto il blocco dell'iniziativa di coloro il cui cambiamento impone dei limiti"	"Quindi noi ci siamo chiesti quali potrebbero essere nel futuro i vari scenari"	"siamo arrivati alla all'immaginazione di tre scenari completamente diversi" // "non sarà semplice perché ci saranno diverse rivolte contro le decisioni più rivoluzionarie e decisioni che più nuove più che nessuno si aspettava."	"Da questa simulazione abbiamo trovato che i possibili scenari che andiamo poi a approfondire meglio anche più in pratica potrebbero essere" // "siamo stati forse un po' troppo ottimisti dicendo che questa sarà la realtà che si respirerà fra vent'anni ma riteniamo che questa sia una strada alla quale prima o poi ci avvicineremo nonostante magari i cambiamenti si vedranno dopo molti più anni"	"Questi invece li abbiamo variati per avere un po' di situazioni diverse"	"Partendo da questo presupposto un po dalle indicazioni che ci sono state fornite allora abbiamo immaginato tre futuri molto semplici "	"presenterò velocemente tre casi che abbiamo considerato per capire come potrà essere la scuola del futuro del 2040 usando questa simulazione."

Figure 15. Structure of the file used to group students' sentences of the final presentation.

While performing the analysis on the students' transcripts, we built an Excel table in which, for each group, we reported the specific sentences or the elements of the presentation in which we recognized the put into action of each future-scaffolding skills. The table was structured as reported in Figure 15.

The database obtained was the basis for the second step of the analysis in which the data were reduced in order to obtain a bigger picture on the skills put into play by the seven groups in their presentations. Hence, from the table with sentences in Figure 15, we derived a table of zeros and ones, like that reported in Figure 16, where the ones where inserted every time in the group's presentation had been found at least an occurrence of the specific skill.

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
St1 - Distinguish between disciplinary details and the comprehensive picture of the future-oriented scientific issue (FoSI)	0	0	1	1	0	0	0
St2 - Unpack the FoSI in simpler, addressable parts	1	0	1	1	0	1	1
St3 - Recognize causal relationships	0	1	1	1	1	0	1
St4 - Recognize multiple aspects of the problems and their relationships for structuring proper thoughts and articulate strategies and plans for solving them	1	1	1	1	1	0	1
Dyn1 - Move from thinking locally to thinking globally (and vice versa)	1	0	1	0	1	0	0
Dyn2 - Move from thinking at the present to thinking at the future (and vice versa)	0	1	0	1	1	0	1
Dyn3 - Move from thinking at the individual to thinking at the societal community (and vice versa)	0	0	1	1	0	1	1
Dyn4 - Think creatively for imagining new possibilities and concrete actions	0	0	0	1	0	0	1
Dyn5 - Balance the need of aspiring with that of keeping feet on the ground	0	0	1	1	0	0	1
Dyn6 - Think in a multidisciplinary way, breaking down the barriers among disciplines	0	0	0	0	0	0	0
Dyn7 - Move from thinking in terms of necessity to thinking in terms oif multiple possibilities	1	1	1	1	1	1	1

Figure 16. Aggregate table for the future-scaffolding skills put into play by each group (0 corresponds to no skills detected; 1 corresponds to one or more skills detected).

For this analysis we did not distinguish between different amounts of skills displayed. Indeed, following RQ1 (*Did the students put into play future-scaffolding skills during the future-oriented activity? If so, which skills?*), the kind of information we looked for was whether they developed future-scaffolding skills and not how much these skills were manifested in the group presentation.
In this phase, we constructed two kinds of graphs. The first shows the groups that displayed each future-scaffolding skills, while the second indicates the number of structural and dynamical skills displayed by each group. For the latter, given the fact that the possible structural skills are four but the possible dynamical are seven, we realized that it was important to normalize the number of structural and dynamical identified with respect to the total possible number. This choice was made to avoid the risk of misinterpretations, for example considering that on average the groups developed more dynamical than structural skills, while this can be a result only of the different numbers of categories used for the top-down analysis.
The graphs obtained were also used to decide how to present the results. Indeed, we individuated two groups (Group 3 and Group 4) that were particularly suitable to illustrate the coding process. As can be seen from Table 16, we chose those groups since they were very rich in terms of future-scaffolding skills displayed, but also complementary one to each other.
Finally, the findings obtained were compared with the results of the previous study by Levrini and colleagues (2021).

8.2. Data organization, data reduction and top-down analysis of the individual interviews

A similar type of analysis was conducted in the second phase of the analysis on eight individual interviews that voluntary students agreed to perform at the end of the course. The data considered for this analytical step were the response of the students to the semi-structured protocol presented in Section 3.7 in which we asked them a comment on what they had learnt from the course in general and specifically from the future-oriented activity. The goal of this phase was to answer RQ2 (*Were the students able to describe the future-scaffolding skills developed?*), checking whether the development of these competences was something of which the students were aware or not and, more specifically, if they were able to find appropriate words to describe the development of the competences. Moreover, from a first exploration of dataset, we decided to include in the top-down analysis not only the future-scaffolding skills but also the changes in students' future perception, defined by Levrini and colleagues (2021) "widening" and "approaching".
The top-down analysis resulted in a table analogous to that reported in Figure 15, where all the students' sentences corresponding to a specific future-scaffolding skill or change in the perception of the future were collected. From that, it was derived a zero-one table like that in Figure 16, following the same methodological considerations expressed in the previous section. Also, analogous graphs were obtained and commented.

8.3. Comparison between skills put into action by the groups and skills verbalized by the students

From the results of the analysis about the skills put into action, performed on the groups' presentations, and about those that the students were able to verbalize in the individual interviews, the third methodological step consists in the comparison between the two. In particular, we restricted our analysis to four groups (Group 1, Group 2, Group 3 and Group 4) since the eight students who participated in the interview belonged to these groups and we had no students for the other four groups. We built a table to highlight three different cases: 1) skills that were present both in the student's interview and in the relative group's presentation; 2) skills that were present in the group's presentation but that the student was not able to verbalize during the interview; 3) skills that we did not identify in the group's presentation but that the student expressed in the interview. From this table, that we report and extensively comment in the data analysis section, we could identify two emblematic case studies that deserved particular investigation and will be addressed in further research.

9. Data analysis and results

9.1. The future-scaffolding skills put into play by the groups in the final presentations

To answer RQ1, in this section we present the analysis concerning the identification of the future-scaffolding skills put into play by the groups in their presentations at the end of the future-oriented activity.

To make transparent the coding process and to explicit the assumptions, choices, and interpretation we made on the students' words, we report in detail the analysis performed on two groups' presentations, specifically those of groups 3 and 4. As explained in the methodological section, the choice of the groups is motivated by the fact that both groups were very rich in terms of future-scaffolding skills displayed, but also complementary one to each other.

To present the analysis, we report the integral transcript in which we underline the specific sentences coded, the future-scaffolding skills identified, followed by the interpretation that led to that coding. For sake of readability, we divide the transcript in short pieces, but in Appendix G are reported the coded transcripts for all seven groups.

9.1.1. Detailed analysis of future-scaffolding skills exploited in the students' presentations – Group 3

> *So, we chose globalization as the main problem to study. In particular, of the whole globalization we want to study that phenomenon which is leading all populations to a flattening of culture.* ***[St2]*** *So we notice that we no longer have those cultural differences that we think are actually important for each single population.*

The issue chosen by the students is connected to globalization, a word used to describe the growing interdependence of the world's economies, cultures, and populations, brought about by cross-border trade in goods and services, technology, and flows of investment, people, and information. Specifically, of all the problems related to globalization, the group decides to focus on the cultural flattening. This choice makes the complex issue from which they started more addressable in a concrete activity. This "unpacking" of big problems in more specific and addressable ones is what characterizes St2.

> *And so, we wanted to solve this problem and then find a way to prevent this from happening.* ***[St4]***

From the statement of their specific problem, the students outline the aim of their activity, e.g. finding solutions to prevent the worsening of the phenomenon. The distinction between problems, objectives and solutions is what characterizes St4.

> *And so, we came up with the imagination of three completely different scenarios.* ***[Dyn7]***

The group, instead of imagining a univocal future, starts the analysis by presenting three different possible scenarios. This movement from necessity (represented by the imagination of a univocal future) to a plurality of scenarios (a widely mentioned term throughout all the presentation) is the distinguishing element of Dyn7.

> *The first scenario* ***[Dyn7]*** *is quite an extremist scenario* ***[Dyn7]*** *in the sense that globalization takes hold completely. So, the whole world, the whole globe is under the same culture* ***[Dyn1]*** *which can be either a culture that was created from the union of all the cultures that were present, or from a different culture that has*

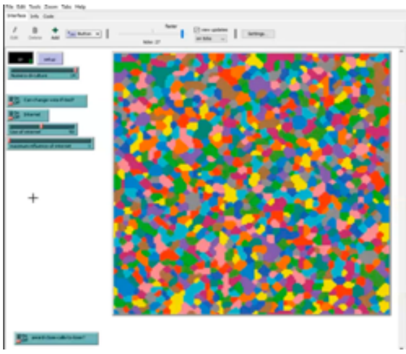
supplanted all the others. Therefore, the populations no longer feel the difference between them. So, the habits are the same, the ways of living and even eating are the same and therefore there are no longer those particularities that were previously special in case one travelled across countries.
The second <u>*scenario*</u> ***[Dyn7]*** *sees the advent of globalization, but this globalization fails to take hold in* <u>*small areas of the territory*</u> ***[Dyn1]*** *where these populations are as if they are closing themselves off as they isolate themselves and therefore try to safeguard their culture ... and therefore they are like the Amish, that is, they* <u>*isolate themselves from the rest of the world*</u> ***[Dyn1]*** *to avoid losing their cultural identity.*
And then instead the third <u>*scenario*</u> ***[Dyn7]*** *which is the one where globalization fails to take hold and therefore a flattening of the culture is not achieved, indeed a situation of equilibrium is reached in which there is* <u>*total coexistence between all cultures*</u> ***[Dyn1]****. So, all cultures remain but they coexist, so there are no longer those clashes in case one is different from the other and therefore there is an excellent and peaceful coexistence, and no culture prevails over the others. So, there is no culture that influences the others, but they are just in contact. So, one can get in touch with them, can get to know them but there is no risk of losing their cultural identity by getting in touch with them.*

The term "scenario" is quite frequent in this section, hence we consider it again a reference to Dyn7, as explained in the previous fragment.
Moreover, in the description of the three possible scenarios, the student emphasizes the difference between a phenomenon occurring at local levels or at global ones. For example, in the first scenario globalization occurs everywhere and a unique globalized culture characterizes "the whole world". In the second, only "small areas of the territory" are prevented from the cultural flattening, because populations "isolate themselves" in an attitude of closure with respect to "the rest of the world". Finally, in the third scenario, islands of different cultures are created and there is not a global cultural flattening. The difference between the second and the third scenarios is that in the second the enclave is closed to the surrounding cultures, while in the third the cultures remain "in contact" without "losing their cultural identity". This tension between local and global, at the basis of Dyn1, is also at the core of the construction of the scenarios and it is what distinguishes the three of them.

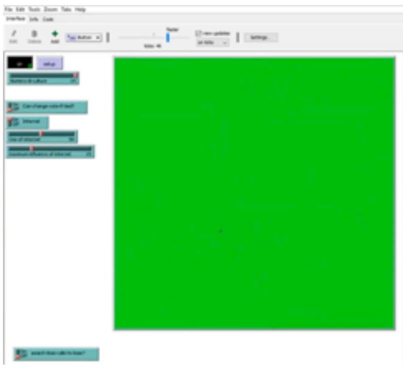
We created a simulation based on the voting model but extending it. <u>*So, I went to intervene on the code by adding the possibility of having more opinions than here*</u>*.* ***[St1]*** *That is, those that for voting would be opinions… which here are instead interpreted as different cultures with a dynamic very similar to that of Voting, except that each patch has the possibility of having patches of more than two different colors around it. And that brings with it the need to change a lot the way the simulation works. Without losing too much in the informatics aspects... the Voting model works numerically by assigning 1 or 0 and then goes to make sums between the neighboring boxes and is very fast. Now, not being able to work with 1 or 0 as in the Voting, given that we have more values, the simulation becomes heavier and slower.* <u>*Here we would also have liked to include the various migrations in the simulation, but they were not easily manageable and, in a model, when you have a data that you cannot manage, it is better not to insert it because otherwise it will create just confusion*</u>*.* ***[St1]***

In this long section, a student presents its elaboration on the voting model to obtain a simulation that includes more than two alternative cultures and a dynamic of influence of opinion at distance that reproduces the idea of the role of internet in the process of globalization. We can notice he moves between model and reality recognizing the differences between the problem he wants to model and the features and limits of the simulation. For example, he explicitly says that he has intervened on the code doing some modifications ("adding the possibility of having more opinions than" in the classic voting model) and that there are aspects of the problem that he had not been able to include in the simulation ("we would also have liked to include the various migrations in the simulation, but they were not easily manageable"). We interpret these as signs of St1 where the disciplinary details are those embedded in the simulations and models, while the comprehensive picture is the problem at stake, in all its complexity.

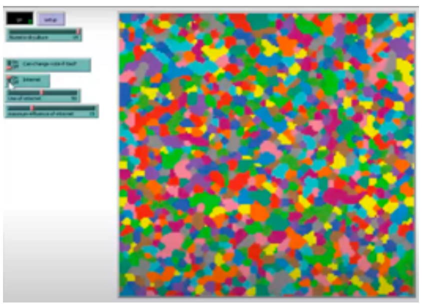
Now, this here is a simple multi-culture voting. ***[Dyn7]***



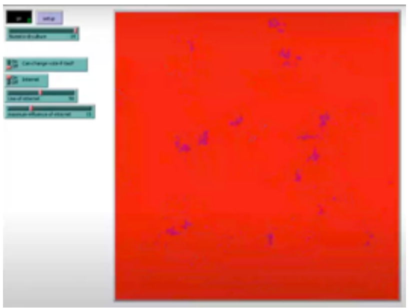
Here, however, we have a voting that starts immediately with the Internet. ***[Dyn7]***



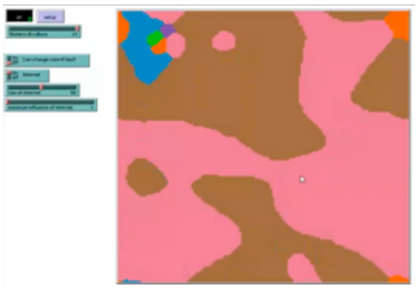
We have inserted this mechanism of the Internet to introduce a bit this theme of globalization. What is the Internet doing? There are two parameters: there is the Internet that can be turned on or off and if it is turned on, those two parameters that can be seen below are activated. One is the use of the internet while the other is the maximum influence the internet can have on a person. The use of the Internet is the probability that a person, so an agent goes on the internet every day, every year, in short, every tick. While the maximum Internet influence is a maximum number of random agents from which that box that agent that access Internet has the possibility of being affected. So, this is a simple voting model where the Internet is turned on from the beginning and then we notice that there is a prevalence, a general flattening of the culture.
Whereas in this instead we wanted to depict a situation which is a little more similar to our world, ***[Dyn7]*** *that is a world that was created without the internet (and therefore at the beginning the Internet was off).*



Then I let cultures cluster and turned on the Internet, somewhat simulating what was the reality... that is, humanity without the Internet was then put in contact. And here too we note that despite the preliminary classification there is a general flattening of the culture.



*We did <u>various tests</u> **[Dyn7]** and saw that every time we turned on the Internet, cultures tended to flatten out. And even here where <u>I have let it cluster first and then I turned on the Internet</u>, **[Dyn7]** with an internet in which it is 50% likely that each agent accesses the internet, it can be seen that even if it is a much slower process, it leads to a general flattening of the culture.*



The student shows the different tests he did that can be interpreted as the different scenarios that can be obtained with the simulation, playing with its parameters. As in the section above, the plurality of possible scenarios that characterizes Dyn7 is at the core of the student's discourse but in this case the scenarios are obtained using a simulation that was specifically developed, while before they were just the result of students' imagination.
Another sentence in which we can read an opening up to the possibilities instead of the deterministic univocity is that in which the student notices a difference between the results produced by the simulation and its expectations and sense of reality:

*This is probably a problem with our model, <u>or a consequence that we do not see now because we are too far in the years</u>… **[Dyn7]** on this it is not up to me to decide. <u>But at a mathematical level it can be understood that this happens because statistically in the moments in which one culture prevails over another the probability that each patch will be influenced by that culture increases and consequently what happens is that we can observe an overall flattening of the cultures</u>. **[St3, Dyn3]***

Indeed, diminishing the probability for one agent of being influenced by a random one via the internet, the student would have expected the survival of more cultures in its setting. Actually, a uniform globalized culture is reached. Firstly, the student's reaction to that is to hypothesize a mistake in his modelling ("this is probably a problem with our model"), but then he envisions the possibility that this behavior is something that we cannot "see now because we are too far in the years". In this way, the student seems to recognize that not always the present can be extended up to the future because there are unexpected behaviors that could occur and that are un-seeable and unimaginable now.

While trying to make sense of this unexpected emergent result, the student engages in a process in which identifies causal relationships within the model, showing a signal of St3. Indeed, he establishes a relationship between causes (the rule at the basis of the simulation) and the effects (the unique culture that he is observing). Before explaining it, he says in advance that his reasoning will be on a "mathematical level", as to say that only what he considers the mathematics of the model can help understanding the unexpected behavior observed. Then, his explanation starts from the moment in which in the simulation there is one culture that "prevails over another". In this case, "statistically", the "probability that each agent is influenced by that culture increases, and consequently what happens is that we can observe an overall flattening of the cultures". In this simple explanation of a complex emergent phenomenon, a causal structure is recognized connecting the rules of the agents (that influence each other) and the collective picture of the simulation (at a preliminary stage when "one culture prevails over another" or at the final one when there is "an overall flattening of the cultures"). In this explanation, which is very typical when agent-based simulations are considered, can also be traced signs of the development of Dyn3, since the student's reasoning moves from the collective unexpected behavior to the individual rules and again to the collective dimension.

> *Therefore, our desirable scenario for 2040 is certainly one in which <u>the various cultures influence each other without, however, none of them prevailing over the others and without a cultural flattening occurring due to globalization</u>.* ***[Dyn1]*** *Hence, it is a future in which political and territorial borders no longer constitute a limit for the exchange of ideas and comparison.*

In contrast with the results showed by the simulation, the presentation continues with a student who recalls their preferable scenario, emphasizing the fact that at a local level the cultures influence each other, but this does not reflect a cultural flattening at global level. This is another sign of the presence of Dyn1.

> *And yet it is still a future in which we remain very attached to our origins and in this future every public event becomes an opportunity for <u>comparison and exchange with people of very different ethnic groups from ours</u>.* ***[Dyn3]*** *And we also thought that a person walks away and tries to hide their culture when they don't feel totally accepted. Our future wants to be free from prejudices and stereotypes and must be characterized by <u>welcoming people</u>.* ***[Dyn3]*** *Hence our scenario is characterized by <u>open mindset</u>* ***[Dyn3]*** *in which we can certainly take the best of each culture with which we come in contact thanks also to new technologies while always remaining very attached to our cultural identity that makes us <u>unique and different from others</u>.* ***[Dyn3]***

The description of the preferable scenario includes the characterization of the role of individuals that need to be "open", "welcoming" and ready for "comparison and exchange" with the others and with the society as a whole. This is what characterizes Dyn3 as the skill that help moving from considering only individuals to considering others and the societal community.

The road to a desirable 2040 will obviously not be easy because there will be several revolts against the most revolutionary and newest decisions than no one expected. ***[Dyn5]*** *For example, the elimination of geographical and political borders or the elimination of the passport or the opening towards immigration for example. These different there will be different ideas in society and this could lead to the creation of factions or in any case points of conflict for different ideas opposed to each other.* ***[Dyn5]*** *There will be two main bifurcation points* ***[Dyn5]*** *in this process of arriving at the desirable future. The first of the scenarios that we have called 1, that is between maximum globalization, that is with one culture that prevails over the others, and scenario 3 which is the desirable one in which all cultures do not influence each other without no one prevails. The second bifurcation point will instead be between scenarios 2 and 3 or between globalization that we could call media, that is with a culture that is more widespread than the others but with minorities still present, and scenario 3 which is the scenario of the desirable future. To get to the 2040 that we want, we will have to rely on the encounter between the different cultures that characterize the world today that could influence each other through social media or even through travel when we will be able to do it again.*

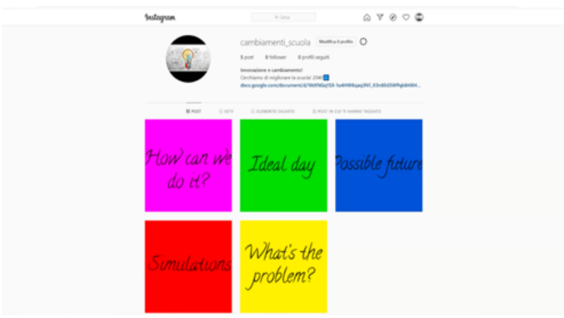
In explicating the backcasting procedure, a student focuses in particular on the obstacles that could be presented to the realization of the desirable future. Indeed, she recognizes that their ideal future includes breaking points that would be difficult to be accepted by governments and by the part of the population with different ideas. Moreover, the group also identifies bifurcation points that in the future could lead to a scenario or another. We interpret this as a sign of Dyn5. Indeed, hypothesizing obstacles, and other facts or decisions that could hinder the realization of the preferable scenario is a way to balance the dream with the concrete circumstances.

The coexistence between these cultures can therefore be of two types: either a real co-living and mutual enhancement of each one, or replacement by a predominant culture and cancellation of individuality. ***[Dyn3]*** *But it will be up to each of us to decide what future we want.*

A student concludes saying that the desirable coexistence between cultures could be of two types: a real co-living where the cultures "mutually enhance each other", or a situation in which there is a "predominant culture" that leads to the "cancellation of individuality". In these two different ways of seeing culture, we can recognize again the signs of Dyn3, because of the relationships that connects the individual, to the cultural community, to the global society.

9.1.2. Detailed analysis of future-scaffolding skills exploited in the students' presentations – Group 4

So as a method of presentation we have chosen to create an Instagram page in which we have inserted <u>five posts regarding our theme</u>. ***[St4]***



In the Instagram profile that the students decided to create to present their work there are five posts (in the Appendix G we also report the extended text of each post, while in this section we only report the words of the students during the final presentation to the rest of the groups). Each of them illustrates one part of their analysis which is articulated in: statement of the problem; simulation used to address it; possible futures; an ideal day in the desirable future; the actions to be done in order to reach that future. Even from this planning of the work and the presentation, we can identify St4 that has at its core the distinction between problems, objectives, and solutions as part of the analysis of a problem.

> *So, the problems we focused on are inherent to school and are two. The first, the main one, concerns the teaching method. The second is the type of grades.* ***[St2]*** *We believe that the classical notional and frontal teaching method is boring and not very interactive and to improve it we should use more digital devices in the classroom. It is a fairly recent issue because we have been at home for many months with the Covid. And the technology turned out to be quite useful, indeed a lot. Technology is certainly a good teaching and learning tool, if clearly combined with paper and therefore with books.*
> *Another point on which we have focused is the question of school grades which we have noticed that let's say they put a little difficulty in the students. So, we are not talking about a total abolition but a passage from votes expressed in numbers to votes expressed in letters of the alphabet, as is the case in America, for example. This is a bit of the description of the post regarding the problem. Now I leave the floor to my colleague who will talk about the simulations we used.*

The general issue the group chose to address is related to school, but in particular two were the problems addressed: the predominance of antiquate ways of teaching and the stress experienced by students also because of the evaluation methods. From the beginning, the students decide to unpack a general problem of interest in simpler, more addressable parts. Hence, we categorized it as St2.

> *Among the various simulations that we thought could reproduce this issue of ours, we chose cooperation because in our opinion it was more suited to this topic.* ***[St1]*** *So as agents we have chosen the greedy cows as, we say, those who support the old traditional teaching methods. Instead, the cooperative cows [are] all those who want to carry on new teaching and learning methods. The grass we thought that could be the support from the students. So, we have already seen the mechanism in previous lessons. However, we have explained it in this way, that is, therefore both, both the greedy ones and the cooperative ones, are nourished by the support of the students.* ***[St3]*** *However, collaborative cows tend to carry out their own initiatives by supporting the will of the students and adapting accordingly. For example, they do not want to impose themselves on the students but prefer to have the necessary support to have the funding deriving from the support of the students to carry out their own changes.* ***[St3]*** *[...] It is as if there was, let's say, the support - I don't know who has already studied Aristotle - in potentiality that becomes active with the financing, so that this process of comparison and change can go on continuously by doing so that the school can always be at the forefront of new technologies. Instead, the other cows impose themselves on the students, they try to get all the support of the students, they prevent the students from confronting each other, perhaps obtaining a school that can better adapt to their new needs* ***[St3]****. Then we attributed some meanings to the variants… for example, we saw the cost of reproduction as the cost necessary to carry out new initiatives. Then we have already established that surely the number of greedy cows will be greater than that of cooperative cows. Then for example we decided that weed energy was student funding. The metabolism corresponds to the fact that with every action the cows, both the greedy ones and the collaborative ones, lose energy which is, let's say, the money they had saved.*

The student explains the simulation chosen to model the problem illustrating the correspondences they have established between the elements of the cooperation simulation and the stakeholders and their relationships in the problem of interest.
In her discourse we can identify widespread signs of both St1 and St3. We recognize St1 since the students use a disciplinary artifact – in this case the simulation of cooperation – to model a problem related to school. In the process of building this correspondence, a relationship is established between the model and the problem, and the causal link between individual behaviors and effects emerges from this back-and-forth movement. She mixes a vocabulary of the model and terminology which is typical of the problem, like teachers who are "nourished by the support of the students" or "cows that impose themselves on the students". Even if she does not explicitly mention causes and effects, we can interpret this movement at the search of analogy as an attempt to relate the causes of a phenomenon in the simulation – features of greedy and cooperative cows – to the causes of a problem in the reality – attitudes of teachers willing for innovations or anchored to traditional methods. Hence, we have categorized these sentences as St3.

> *From this simulation we have found possible scenarios.* ***[Dyn7]***

Here the student starts presenting a plurality of possible scenarios. As already argued for group 3, this is a sign of Dyn7.

> *The most desirable is the balance between the old traditions, the old teaching methods, and the more innovative ones, because we think that both can be useful and fundamental to reach a type of school, of modern teaching more suitable for students.* ***[Dyn5]*** *The other two are more, let's say, the extremes, that is, only the new teaching methods prevail; therefore, some modalities that are useful for teaching are abandoned and perhaps the risks due to new technologies increase.* ***[St4]*** *And instead on the other hand we have the lack of imposition: the new methods fail to impose themselves in schools and we do not get a change.*
> *And then we started from the fact that a possible solution of the simulation that can then be applied in reality is that the cost of reproduction could be lowered. For example, in practice this can amount, for example, to ensuring that the government can bear the costs necessary for new changes and thus making it easier and faster to implement new methods within schools.*

Even if the group's presentation had begun by stating that the problem of school is that "the classical notional and frontal teaching method is boring and not very interactive" and to improve it "we should use more digital devices in the classroom", the desirable future that the students envision is characterized by an equilibrium between tradition and innovation. In this way, we recognize Dyn5 because instead of an exacerbation of a position (for example, the exclusive use of technologies in education settings), they imagine a future in which the innovative methods are counterweighted using more traditional ways of instruction. This consideration is also based on the students' analysis in terms of risks and benefits of technologies which can be interpreted as a sign of St4.

> *We have discussed that during this pandemic the use of technologies is becoming more and more recurrent. In particular, we have also considered how probably these new technologies will tend to become almost everyday life, perhaps even starting from middle school.* ***[Dyn2]*** *In fact, we have considered the use of technological tools starting from the lower levels of education because spending many hours in front of screens from an early age*

can also lead to posture defects or even damage health. So, probably there will be strong opposition which will also limit the use of technology during the first years of school. In our opinion we will probably reach a level in which electronic devices such as computers and tablets will also be used with a good sequence during lessons starting from middle school. We were also imagining a possible platform that allows a better synergy so that the teacher can also enter the work of each student to see in real time what they are doing, also allowing to better understand the reasons for which maybe they are stuck in a problem and can't move forward.
Furthermore, we also imagined that the new teaching methods adapt to a new time management that for us needs to be improved a little. In fact, the lessons are too dense and very often it is difficult to grasp all the notions. We also imagined longer lessons that contain the same amount of information so that the latter are diluted over time. Obviously, we realized that in addition to being the possible solution to shorten the training plan perhaps by removing some more nationalistic elements that will then be forgotten, it could also be convenient to use the afternoon so that we can also organize hours in which the students can also come together to study in groups, perhaps even with some professors. We have also noticed that in this way the time available could also grow exponentially because a quality study would be made that would allow us to reduce the time for self-study. But this will then be better narrated by my mate.
We also noticed how having the afternoons available to students would be even more incentivized to take courses that could lead them to approach experiences that they have never done in their life and in doing so they could also have a better idea of which may be their attitude. It could also be useful for orienting them to a university course. In addition, since the students will spend so much time at school, would become necessary physical activity. Consequently, we have also imagined a future in which schools organize sporting moments even within the lessons as happens for example in America with basketball...
Furthermore, with the increase of afternoons spent at school, human relationships would be favored both among students and between professors and students, making sure that we also go to re-evaluate what is our image of the teacher who otherwise is seen as an austere character who wants to put ourselves in difficulty when in reality is in any case a person who perhaps shares our same interests and a better bond could also be created. Furthermore, we also imagined that in the future school trips or internships could become more and more present to acquire new knowledge much more varied than those that can be learned at school. <u>We also paid particular attention not to imagine a future that would require large funds from the state because we realized that it would take much longer to implement them all within our future and consequently, apart from what concerns new technologies, we imagined a future that was achievable even without large funds</u>. ***[Dyn5]***

The student illustrates the features of their desirable scenario and starts with a consideration that signals the presence of Dyn2. Indeed, the trigger for the use of technological devices in the classrooms comes from observing what is happening during the pandemic in which “the use of technologies is becoming more and more recurrent”. From this observation, he imagines that “these new technologies will tend to become almost everyday life”. Extrapolating trends from the present and projecting them to the future is a very common way of building scenarios and it can be a sign of Dyn2, even if there is not yet an explicit back-and-forth dynamic that will be more evident in the next paragraph.
At the end of the description of the ideal scenario, the student shows again Dyn5 because says that in dreaming about an ideal school they have considered practical constraints like those related to funding.

We tried to imagine what a day could be for us, as students, in our best future, in case all our projects have gone in the best way. So, we thought that in the morning there could be lessons like now but from 9 a.m. to 1 p.m. so 4 hours... so start a little later than now... okay, let's forget the virus situation because in our ideal future the pandemic should be over… so let's imagine a normal day without virus. So 4 hours of lessons for all that end at

1 p.m.. Then we have a lunch break to eat and rest. And then in the afternoon we thought that going back to school could actually be very useful. Clearly the lessons in the morning are lessons in which things are taught but there is also a lot of talk about the applications. Because in the afternoon from 2 to 5 p.m.… then it is clear that we have given a bit of an image but of course you can think about how to do it better... but during these hours, laboratory activities or meetings with experts can be carried out, or trips or visits to museums, sports… these are all activities that in the afternoon it is important to do as well as for example study in pairs or even with professors. In this way the human relationship is valued, and we move away from a concept of frontal teaching but a teaching that aims more at education and less at leading you to know notions that are often forgotten. Then from 5 p.m., let's say, the personal activities can begin. So, if one needs further study, they can study again or rest or carry out fun and relaxation activities. This is an aspect that we think it is neglected today, time for oneself today is a bit neglected because in any case we are always busy with tests during the year. Maybe even the management of the school timetable as it is distributed throughout the year... maybe avoid leaving three summer months but dividing it better could be very functional. And then the evening is time to dedicate to friends or family which is increasingly important in life. This is a bit like our ideal day. For the conclusions I leave the floor to my colleague.

In this fragment we have not identified future-scaffolding skills but in the description of the ideal day of this student an issue of time management emerges very clearly. In the era of the pandemic and of the present shock (Levrini et al., 2020), these students dream about a change of routine for their life. Despite the common idea that the youngsters are getting sick of school and want to study less, these students are dreaming about a future in which they are at school for the most part of their day. Indeed, learning, understanding and thought need time. Another important point raised by the students is the value of a school that supports personal and social relationships among peers and between students and teachers, in a perspective of educational alliance. This way of students to imagine the future after the pandemic would deserve a deeper investigation.

*Then I will mainly talk about the main obstacles and what we can do. First of all, support is needed from the government, from <u>the Ministry to increase funds for the school, to set up schools or projects that individual schools cannot do</u> **[Dyn4]**. For this <u>it is necessary in a sort of activism from students and teachers who can start petitions or even movements on social media or mass media</u> **[Dyn4]**. In this way, many more people would encounter these ideas and maybe it would also spread faster since we can exploit a tool [the social media] that is still very prevalent today in the life especially of young people. Then there would be the objection that the school curriculum should not be cut. To cope with this problem, <u>innovative schools could be set up in Italy to obtain data that can actually be compared to those that exist now with traditional schools</u> **[Dyn4]**. In this way one could see if the school program is already ideal as it is now, or if it can be changed and what needs to be changed. Furthermore, it is also difficult to find teachers willing to try new teaching methods. In this case, <u>projects or courses could be set up for the teachers themselves so that they can confront each other to devise new teaching methods and perhaps even discuss them with the students to have their approval</u> **[Dyn4]**. Another important point is <u>peer instruction</u>, something that is already present now but is not being exploited enough. For this it would be useful to publicize these events and make them common in all schools. Finally, <u>an effort is needed on the part of everyone, especially the students. In fact, it is the students themselves who mobilize themselves to bring about a change in Italian education</u> **[Dyn4]**.*

In the back-casting phase of the future-oriented activity, the students imagine different creative actions that could be tackled to reach the ideal scenario, showing the development of Dyn4. In particular, they identify actions at different levels and that have to be addressed by different stakeholders. There are actions at an institutional level that only the government and political stakeholders can address; it is the case of the setting of experimental schools and projects by the Ministry of Education. Then, there are actions that expert stakeholders - like the heads of schools or teachers - can do; for example, the student cites the introduction of peer instruction moments or the institution of continuing education projects to keep the teachers up-to-date about technology-assisted methodologies. Finally, there are actions that also students can do, by themselves or in alliance with the teachers, such as signing petitions. They talk about "activism" and "mobilization" "to bring about a change in Italian education".

> *For this it is necessary to awaken in a certain sense the students from the passivity that harbors these days. More than passivity I would say indifference towards the school, since now it is almost like torture many times. For this we need movements that can reach everyone, so that they realize that the school can change, and they can do something to help* ***[Dyn3]***.

The student remarks the idea that not only the students more involved should take part in this form of student activism, but every student should be reached to "realize that the school can change, and they can do something to help". This activism is a way, for this group, to convey the idea that the single students, as agents, are able to impact and change the society in which they live. In the critique to passivity and indifference we recognize the sign of Dyn3, because they are wishing for a transition from individualism to an attitude that really aspires at influencing the social setting.

9.1.3. Future-scaffolding skills into action: Results of the analysis of the seven groups' presentations

After having presented the rationale behind the coding procedure on the final outputs of two groups, we discuss the results of the coding performed on all the seven presentations.

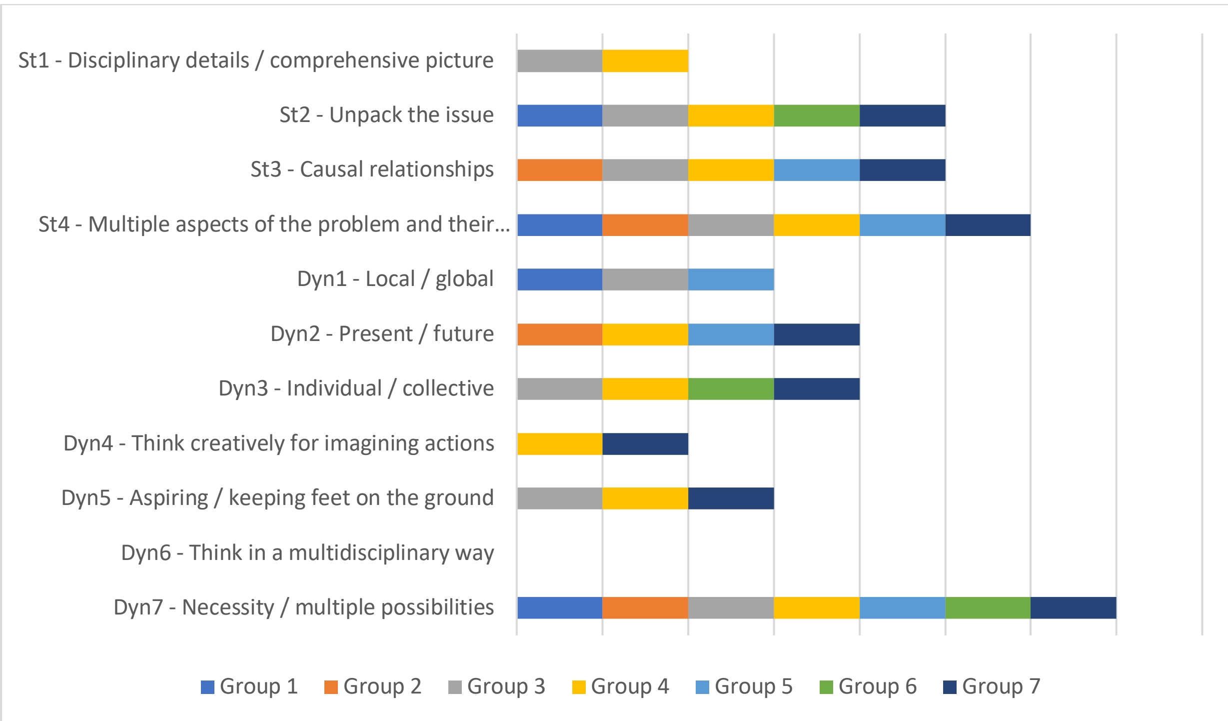


Fig 17. Distribution of future-scaffolding skills detected in the final presentations of seven groups of students.

In Figure 17 is reported the graphic of the skills displayed by each of the seven groups. From here we can do some observations. All skills, but Dyn6 could be detected in at least two presentations; six skills (St2, St3, St4, Dyn2, Dyn3, Dyn7) were traced in more than half of the groups; Dyn7 was the only skill recognized in all the presentations, followed by St4 that only one group did not put into action.

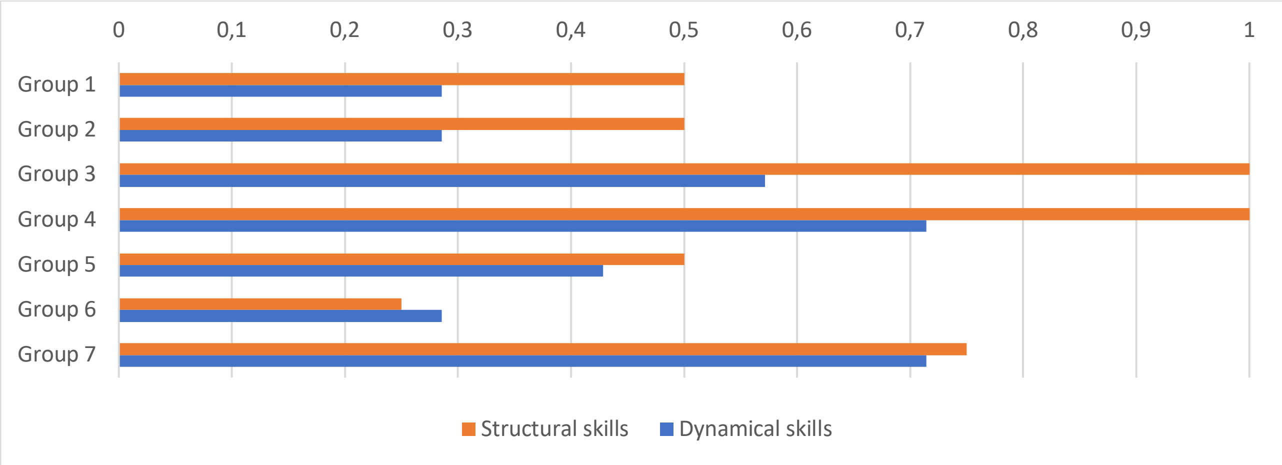


Figure 18. Structural and dynamical skills detected in the final presentations for seven groups of students, normalized between 0 and 1 (1 for structural means that the group has put into play all 4 structural skills, 1 for dynamical means that the group has put into play all 7 dynamical skills).

In Figure 18 we report the summative graphic with the structural and dynamical skills per group, normalized between 0 and 1 (1 for structural means that the group has put into play all 4 structural skills, 1 for dynamical means that the group has put into play all 7 dynamical skills). While Figure 17 is organized per skill, in Figure 18 we can see more clearly how the skills are distributed in each group. In particular, we can notice that there are groups which are very equipped of both structural and dynamical skills (like groups 3, 4 and 7), while others seem quite poor for what concerns the detection of these competences (like group 6).

If from Figure 17 we can count 23 occurrences of dynamical skills against 18 of structural, when we normalize these values (as in Figure 18) weighting them with respect to the total possible structural skills (4) and dynamical ones (7), we can notice that for all groups but the sixth, structural skills are more recurrent than dynamical ones. These results are novelty with respect to the original study by Levrini and colleagues (2021). In that paper they write: “Frequencies of occurrence cannot be compared between structural and dynamical skills due to the difference in difficulty of describing them. The dynamical ones are easier to describe even without specific questions in the data collection tools since they require a narrative style. On the other hand, description of structural skills can require specialized language. On the basis of these remarks, the fact that many students show structural skills is in itself a very interesting and positive result”. In our findings, the high frequency of structural skills confirms the importance of the scaffolding provided by a purposefully designed activity to trigger them. Indeed, as it will be illustrated in the discussion (Section 10), the very same structure of the activity invited the students to structure their thinking about the future-oriented issue in terms, for example, of distinguishing between problems, causes, goals, solutions, actions.

9.2. The changes in future's perception and the future-scaffolding skills verbalized by the students in the final interviews

To answer RQ2, we analyzed the individual interviews carried out at the end of the course with eight voluntary students. The analysis was conducted to understand how students talked about the competences they developed through the course, and to which extent they were aware and able to verbalize the development of the competences. In this phase of the analysis, we realized that not only the future-scaffolding skills were mentioned by the students, but they also talked about other aspects that referred to the impact of the module in shaping their perception of the future. In the study by Levrini and colleagues (2021) these changes were conceptualized under the name of "widening" and "approaching", the former relating to an opening up of knowledge and perspective on the future-oriented issue and the ways to tackle it, the latter regarding an increasing of personal involvement toward one's own future that, from far and unimaginable, becomes thinkable, approachable through concrete actions and ultimately within their reach.
To make more transparent the coding process on the interviews and give back the "flavor" of students' words to describe their development of structural and dynamical skills, and their change of future perception, we report in Table 14 a quote for each category.

Table 14. Examples of students' verbalization of their change of future perception (widening and approaching) and development of future-scaffolding skills (structural and dynamical).

Description of marker	Examples of students' sentences
Widening	
(Wid0) Widening in the amount of knowledge about the disciplinary contents of the FoSI (Future-oriented Scientific Issue)	"I have discovered a new, a new topic, let's say, a new topic in science that I think, and hope will be my future domain." (Alessio)
(Wid1) Widening in the amount of knowledge on future thinking, provided by futures studies	"I learned the concept that from a single event there can be, let's say, ramifications and therefore different possibilities, different futures, actually" (Giacomo)
(Wid2) Widening in the range of new ways of addressing and looking at the FoSI	"Simulations are tools that can be used for different points of view and we can look at them from different points of view, in different ways" (Alessio)
(Wid3) Widening in the range of possible roles of non-expert stakeholders (e.g. citizens, policy- makers) for addressing the FoSI	/
(Wid4) Widening in the range of possible roles of expert stakeholders (STEM researchers and other experts in the field) for addressing the FoSI	"I learned a lot from the moments when professionals working with simulations talked. It was also very interesting to hear how they used the simulations and a little to discover their work in general." (Elisa)

(Wid5) Widening in the range of possible actions, strategies and concrete solutions that can be undertaken to address the FoSI	/
Approaching	
(Ap1) The future became closer to students' imagination, i.e. from far and unimaginable, it became thinkable to them	"I experienced this freedom from the point of view of imagining and thinking which is less bound by rules and limits, it is not limited here." (Giacomo)
(Ap2) The future became closer to students' present reality, i.e. it became approachable through concrete actions that can be undertaken in the present	"it is you in the first person who can act and in most cases even change things. So I would start acting first on the things I'm sure I can act on and then maybe think about what I can do from the outside" (Jonathan)
(Ap3) The future became closer to students' personal, social, professional growth path, i.e. it became within their reach and they found ways to see themselves as agents of their own future	"We have always been taught to think in pieces... in the sense... one goes to primary school, then to middle school, then to high school, and then chooses the university. In my opinion, instead, we need to start connecting things. That is, we get to the end of our high school, we must start dedicating ourselves to the things that really interest us and not every time to look at everything in such a broad way. In my opinion this course has really taught us that you can start making choices for your career. That is, if one knows what he wants, what he wants to aim for, what his interests are, he can start looking at what can be useful for growing those interests." (Valeria)
Structural skills	
(St1) Distinguish between disciplinary details and the comprehensive picture of the FoSI	"As skills, I learned to have an overview that allows me maybe to focus on a problem at the beginning, maybe wait a bit, but try to understand it from a wide enough perspective and then go into it in detail and understand what happens" (Davide) [from the big picture to the details] "I learned to see the different dimensions and that from a very small thing, which was a theoretical thing - because in the end they are small operations - you can move on to study things even in large" (Valeria) [from the details to the big picture]
(St2) Unpack the FoSI in simpler, addressable parts	"Maybe at the beginning I said: "Ok the topic is very vast, it is impossible that we will discover everything because it is really difficult so let's eliminate some parts" like we decided that these parts we do not do, we do these ..." (Davide)
(St3) Recognize causal relationships	/
(St4) Recognize multiple aspects of the problems and their relationships (e.g. distinction between problems, objectives, solutions or between pros and cons) for structuring proper thoughts and articulate strategies and plans for solving them	"As a group we addressed the problem of the distribution of wealth, and we had to see all the contexts where this problem impacted. At the beginning I thought about how to order the concepts by importance and what to do in practice ... that is, I tried to build a structure of the problems and sketching the possible solutions" (Davide)
Dynamical skills	
(Dyn1) Move from thinking locally to thinking globally (and vice versa)	"We used agent-based simulations and we started from the particular, we gave instructions to the single agents, we saw how they interact and then we evaluated the general trend" (Federica)

(Dyn2) Move from thinking at the present to thinking at the future (and vice versa)	"It was useful to me to think first about the future and then think about how to get there. That is, I was interested in this thing of starting from the end to understand what to do to get there. Because in my opinion we are usually used to thinking about the present, what to do in the moment, even losing a little bit of the final goal. But in my opinion, if we kept better in mind what we want to achieve next, it would be easier to understand what to do instead of doing the opposite." (Elisa)
(Dyn3) Move from thinking at the individual to thinking at the societal community and/or the other stakeholders	"Agent-based modeling really depends on the agent, in the sense, not on a global thing but you have to look at the individual. So based on the behavior of each individual, one can study modeling. So, you don't have to think globally but what each individual character does that we put into [the simulation] and then based on the behavior of each individual you can study what happens." (Valeria)
(Dyn4) Think creatively for imagining new possibilities and concrete actions	"The simulations have been used by scientists to study certain phenomena, to prevent their occurrence, then to carry out a process of let's say knowledge. We too were used to evaluate the future and understand how to make concrete actions." (Federica)
(Dyn5) Balance the need of aspiring and desiring with that of keeping feet on the ground	"So, for that we tried to choose something that would go against globalization but at the same time be open to change and therefore lead us both to have a cultural identity but at the same time to have a baggage that could help us grow." (Valeria) "Being too rigid you risk staying in the same place: you need to stay flexible." (Jonathan)
(Dyn6) Think in a multidisciplinary way, breaking down the barriers among disciplines	"I liked it a lot because we found ourselves making reasonings that didn't even seem related to physics. One takes a problem that is not physical, because it is not physics in terms of numbers and equations and formulas. But then you try to take a general problem, which seemed to us almost to be talking about philosophy when we did this work, and then try to put it in a kind of table and then schematize everything in a model" (Valeria)
(Dyn7) Move from thinking in terms of necessity to thinking in terms of multiple possibilities	"Talking to each other we found some problems that were… that seemed very far from this method of resolution, but which could not give the solution, but still show us a scenario with this method" (Emilia)

In Figure 19 we report the graph for skills and changes in future perception claimed by the students in the final interviews.

From Figure 19 we notice that the most frequent is Dyn7, the skill to pass from thinking at a deterministic future to a range of possibilities, with all students who said in the interviews to have become aware of this distinction. Dyn7 is followed by St4 and Wid0, with six students who said they have learnt to distinguish between problems, goals, and solutions, and to have widened their knowledge about the topic of simulations which they did not know before the course. We can observe that all skills but three were cited by the students in the interviews. These are Wid3, about the role of non-experts in the future-oriented scientific issue, Wid5, about the concrete strategies to address the problem, and St3, about the recognition of causal relationship in a topic.

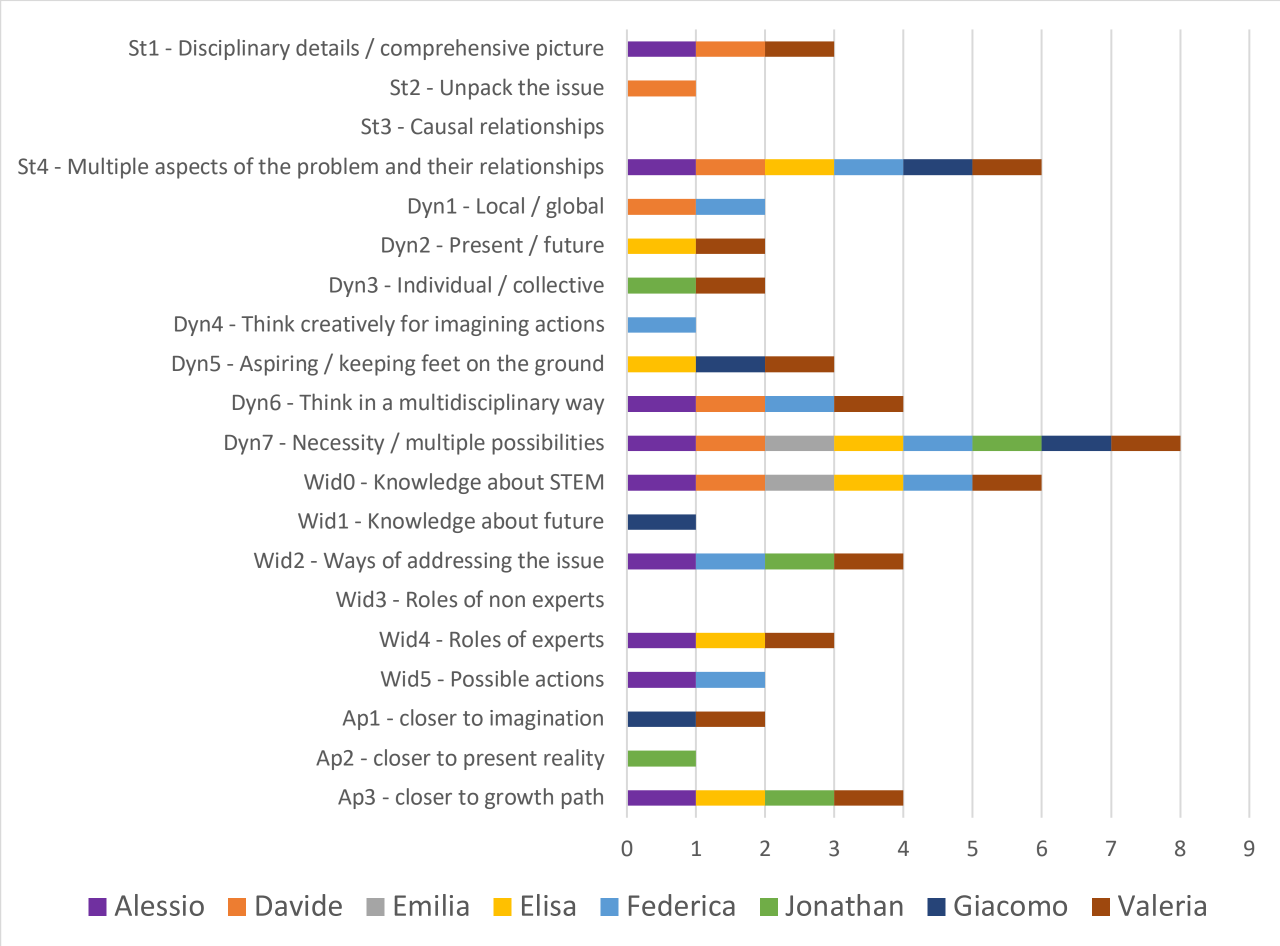


Fig 19. Distribution of future-scaffolding skills and changes in the perception of the future perceived by eight students.

To have a broader picture on the distribution of the four macro-categories, in Figure 20 we report the aggregate distribution of widening, approaching, structural skills and dynamical skills normalized between 0 and 1. Here we notice that on average dynamical skills and widening are the more represented macro-categories, while structural skills and approaching are the less frequent. Indeed, all students perceived to have gained at least one dynamical skill (specifically, from Figure 19 we know that all students had Dyn7) and to have widened their future perception. Then, 6 students had at least one structural skill and 5 recognized the future approaching to themselves. Even if the macro-category of approaching is, on percentage, the less represented, we recall that it refers to a personal, private, and imaginative dimension and the fact that it appears in 5 students out of 8 is an impressive result for an 18-hours online course.

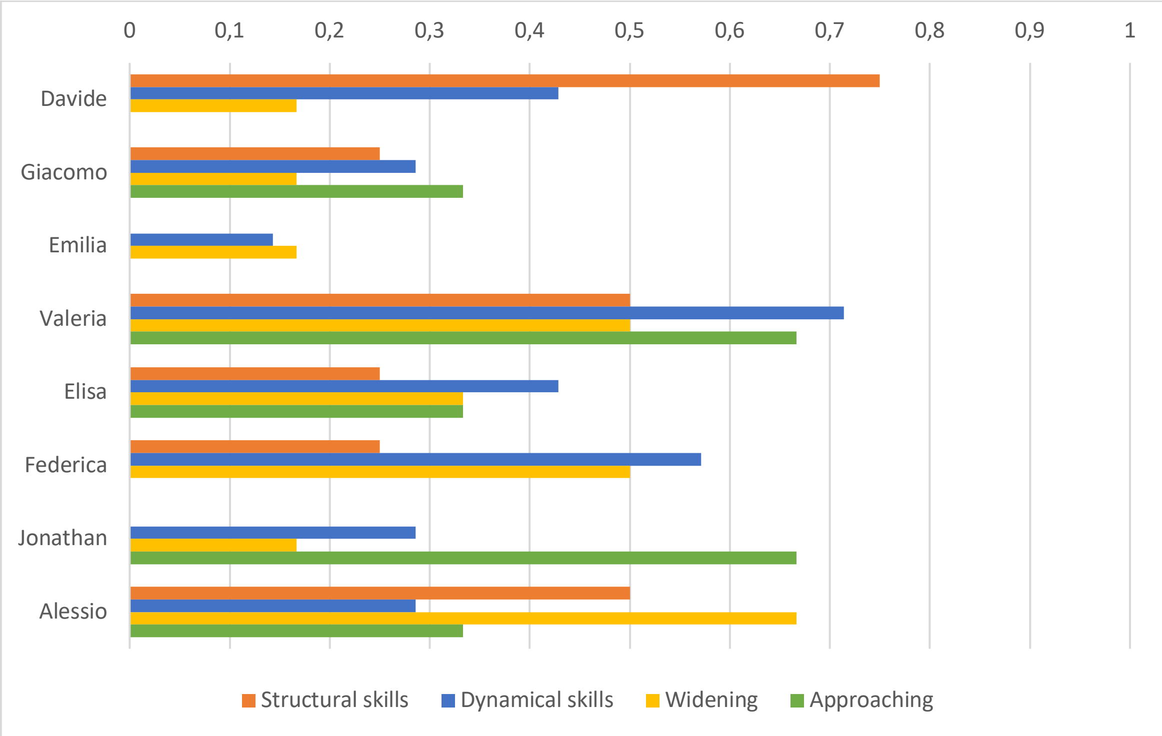


Fig 20. Future-scaffolding skills and changes in the perception of the future perceived by each student, normalized between 0 and 1 (1 for structural means that the student has perceived all 4 structural skills, 1 for dynamical means that the student has perceived all 7 dynamical skills, 1 for widening means that the student has perceived all 6 nuances of widening, 1 for approaching means that the student has perceived all 3 nuances of approaching).

9.3. Comparison between skills in action developed by the groups and skills verbalized by the students

After having presented separately the skills put into action by the students in the presentations and those perceived by them and expressed during the interviews, we provide some criteria of comparison to highlight similarities and differences.

We notice that in both cases the most detected skill was the dynamical one on the plurality of scenarios (Dyn7), followed by the structural skill on the organization of the inquiry with the statement of a problem, the identification of objectives and the search for solutions (St4). As we briefly commented, we can suppose that the same structure of the future-oriented activity was something that triggered the development of this competence, but we will make this more explicit in the Discussion (Section 10).

The main difference we see is that in the students' presentations we could not detect any Dyn6 while this was an important aspect in the interviews in which a specific question asked the students to reflect on the disciplinary tools and ways of reasoning they had taken into account to do the activity. Conversely, in the interviews the students did not refer to have obtained St3, while the recognition of causal relationships was at the heart of all but two presentations. If we consider the relative frequencies, in the presentations were detected much more structural than dynamical skills, while in the interviews the students gave slightly more emphasis to the development of dynamical than of structural skills. This difference between the distribution of the two macro-categories of future-scaffolding skills makes us reflect. If, with tailor-made designed activities, the students can be led to develop structural skills and put them into play when they have to scaffold their thoughts about a problem, when we ask them to describe these competences, things change. Indeed, it seems that they lack words to describe the achievement of structural skills, even if they brilliantly put them into play during the group activity and also individually in some parts of the interview more focused on conceptual aspects. The case of St3 on causal relationships is remarkable: while the students extensively reasoned on the causes of their problem and the possible changes to create desirable effects, in the interviews none of them recognizes this as an importance competence to analyze a complex issue.

The samples for the two analysis – skills into action and skills perceived – are obviously very different. In the case of the analysis of group presentations we had data for all the seven groups. Here, following Levrini and colleagues (2021), we took the methodological decision to look at the skills put into action as a result of the students' interaction in the groups. Indeed, even if the coding was performed on specific sentences pronounced by one student per time, we assume that the choices made for the final projects were based on shared decisions within the groups. In this sense, we considered the skills put into action as skills achieved by the group, rather than specific students. On the opposite, for the individual interviews we have only the data for the 8 student who decided to take part in this optional activity but, in this case, we were able to assign the skills to one student and not generically to their group. We can focus only on future-scaffolding skills, leaving behind widening and approaching: the result is plotted in Figure 21, where we report the distribution emerging from the interviews and that resulting from the analysis of the groups' presentations.

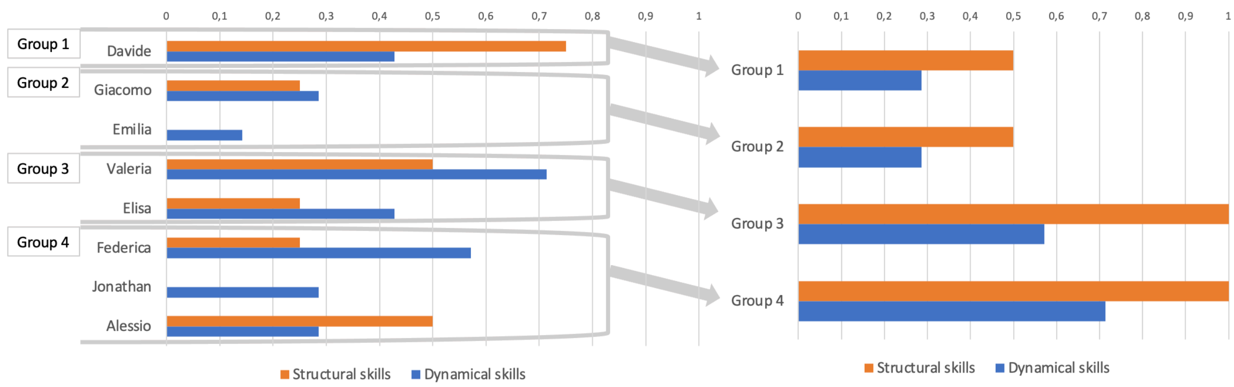


Figure 21. Distributions of normalized future-scaffolding skills in individual interviews (on the left) and in groups' presentations (on the right).

From Figure 21 we notice that many students show gap between the skills put into play during the group activity and those perceived and verbalized during the individual interview. For example, Federica results having a much poorer individual profile than that of the group she belonged: indeed, while in her group's presentation we could detect 4 (out of 4) structural and 5 (out of 7) dynamical skills, in the interview she only said to have developed 1 (out of 4) structural skill and 4 (out of 7) dynamical skills. While Federica's profile exemplifies the fall of structural skills, Davide's one shows an opposite trend. In his case, his group only put into action 2 (out of 4) structural and 2 (out of 7) dynamical skills, but in the individual interview he resulted being aware of the development of more competences (3 structural and 3 dynamical). The analysis of these two emblematic case studies will be addressed in further research to interpret the significant gap between the competences "in action", displayed and put into play in the presentations, and those that the students could recognize and express with their own words during the interviews.

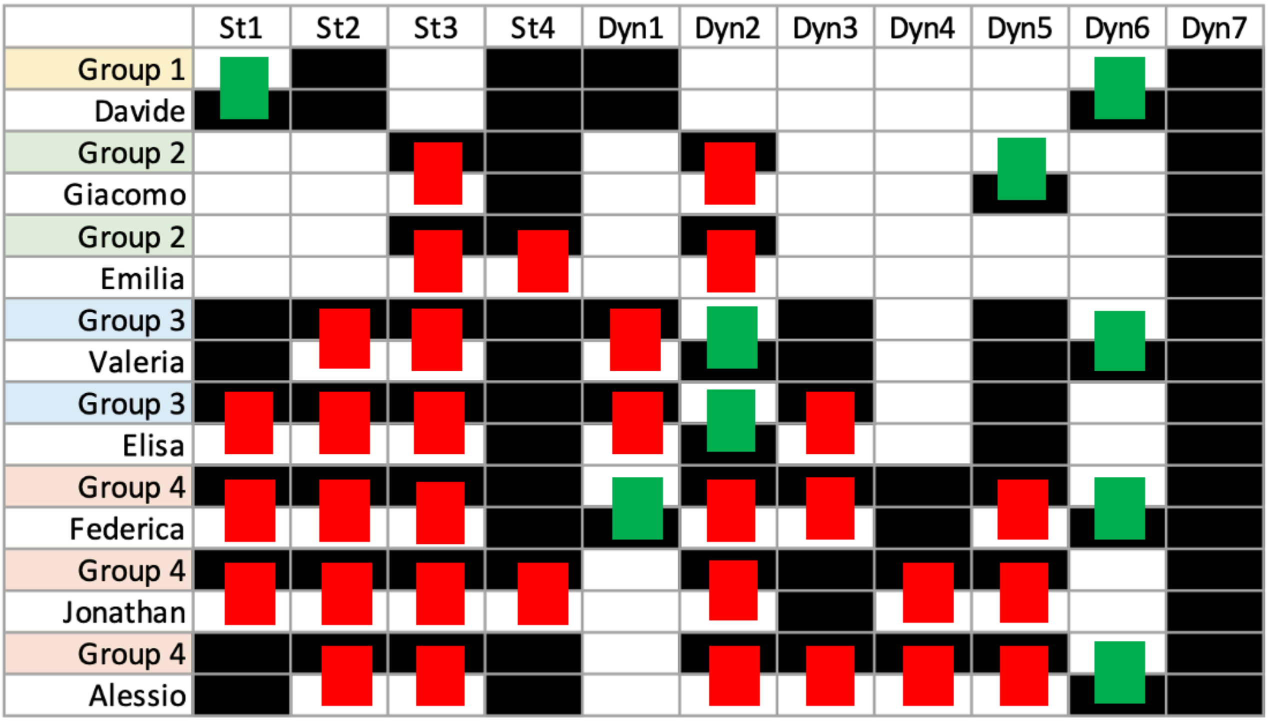


Figure 22. Comparison between skills put into action (groups rows) and skills verbalized (students rows). The skills detected are marked in black; the absence of skill is left white. In red are marked the skills that the students did not verbalize in the interview but were put into action during the presentation; in green are marked the skills verbalized by the students but that were not detected in the presentation.

This is even more evident if we look at Figure 22, where we do not only report the number of structural and dynamical skills as macro-categories. We mark in black the skills that can be detected in the group presentations and in the interview, while red and green are used to signal a difference between the skills' verbalization and put into action. More specifically, red means that the student did not verbalize the skill that his/her group had put into action during the presentation; on the opposite, green is used to signal the cases in which during the interview the student has cited a competence which was not detected in his/her group's presentation.

10.Discussion

To better understand the findings and the answers to the first two research questions, a deeper discussion is needed on the role of the future-oriented activity (and of computational agent-based simulations) in triggering the putting into action of the future-scaffolding skills. Hence, we discuss in depth each future-scaffolding skill, to highlight the potential of agent-based simulations in general and specifically of our future-oriented activity to foster their development and put into action.

<u>(St1) Distinguish between disciplinary details and the comprehensive picture of the future-oriented scientific issue (FoSI)</u>

The simulation was a way for the students to start from a big problem of their interest and to address it using a STEM tool. In this way, they were able to tackle complex issues that touched societal and political dimensions by focusing on the disciplinary details required to enter the dynamics of simulations. Some groups inspected the simulations in their computational aspects. Others observed the graphics obtained and evaluated trends, from a mathematical point of view. Still others questioned the dynamics of interaction from the point of view of physical modelling. Furthermore, some groups were able to identify the limits of the approach based on simulation to address the complex problem: this means that they recognized profoundly the difference between the disciplinary thickness provided by the simulation, and the comprehensive picture of the problem they wanted to address.

<u>(St2) Unpack the FoSI in simpler, addressable parts</u>

A frequent characteristic in many future-oriented topic is their complexity and multidimensionality. In front of an issue like that, this skill is needed to realize that, to address such a complexity, the problem needs to be broken up in simpler components. Simulations were very important for the students in this process. Indeed, for some groups the choice of an elementary toy simulation to model the problem was a way to recognize that the simulation could capture one aspect of their big problem of interest. Moreover, some students realized that different simulations could help investigating different aspects of the problem, without expecting that a single simulation models the issue in all the desired details.

<u>(St3) Recognize causal relationships</u>

To manage the complexity of future-oriented topics, the identification of a phenomenon as cause and effect of others is essential not only to structure proper thoughts on a problem but also to build future scenarios. As the literature in science education has studied (e.g. Braaten & Windschitl, 2011; for further references we send the readers to Chapter 2), causal explanations can be of different types. In our case, some groups limited themselves to establish causal relationships for their problems only following their common sense. It is the case of the students of group 5 who, talking about their problem of overpopulation, say: “if nothing is done to improve the situation, so if we do not plant trees and if better decisions are not made, everything is destined to fall apart”. In this case, there are very general causes (the refusal to do some actions and make some decisions) and very general effects (the worsening of a situation) but there is not any real explanation for this connection between causes and effects. Other groups instead give us an example of reasoning on the actual mechanisms that connect causes to their effects. The way for them to establish this causal relationship is investigating the model at the basis of the simulation ("at a mathematical level it can be understood that this happens because statistically in the moments in which one culture prevails over another the probability that each patch will be influenced by that culture increases and consequently what happens is that we can observe an overall flattening of the cultures"). Differently than before, in this case the group distinguishes causes (mechanisms of interaction among the agents) and effects (local and global cultural flattening).

(St4) Recognize multiple aspects of the problems and their relationships (e.g. distinction between problems, objectives, solutions or between pros and cons) for structuring proper thoughts and articulate strategies and plans for solving them

The last structural skill can be interpreted in our context as the ability to organize in a logical way the inquiry about the future-oriented topic. It is the second most frequent skill traced in the groups' presentations and this can be explained since we had designed the future-oriented activity itself with a structure that could support the development of this competence. Indeed, the activity required to pass from the formulation of a problem to the search of a tool to investigate it, from sketching scenarios to outline a possible path to reach the desirable future. However, the interesting thing is that it seems that the students internalized the difference between these layers of analysis: they used them to structure their presentations and to describe their way of addressing the activity. In some cases, the groups also focused on addressing the pros and cons of something to evaluate the state of the art of an issue or to decide between alternative solutions.

If we take at a look at the four structural skills together, we can see an overarching picture. The first two skills are two different ways to *handle complexity*: the first consists in recognizing the disciplinary details, while the second relates to the decomposition of the big issue in more addressable sub-themes. If for the first the emphasis is on the distinction between the trans-disciplinary picture and the disciplinary details, the second doesn't touch the disciplinary dimension and address an issue of manageability, with a complexity that needs to be reduced of "size" to be handled. On the other side, the third and the fourth skill are about *diving in complexity*. Indeed, here the emphasis in not on the sub-components of the problem but on the relationships among them. While in the third skill these relationships are needed to connect causes and effects, with the fourth one focuses more on logical relationships between problem, objectives, and solutions or, for example, between pros and cons. The four skills together build in this way a rational scaffolding of the future-oriented issue constructing its structure. To move up and down of the scaffold, in order to construct the building, other skills are needed, the dynamical ones.

(Dyn1) Move from thinking locally to thinking globally (and vice versa)

In some presentations, the students were able to consider local and global aspects of the problem they chose and to connect them. The simulation was for them a way to navigate across these two layers. Indeed, this is a crucial feature of agent-based models: there are rules that act locally between the components of a system, and we observe behaviors at a global, systemic level. The connection between these two layers is not trivial and usually involve the construction of mid-levels (Levy & Wilensky, 2008). However, this competence was not only recognized when the students reasoned explicitly about the functioning of the simulation but also in other occasions, for example when Group 5 distinguished between the role of local actions and global policies in achieving a goal.

<u>(Dyn2) Move from thinking at the present to thinking at the future (and vice versa)</u>

The problematization of the relationship between present and future is at the core of the design principles of our future-oriented activity. To act meaningfully in the present, the future must be taken into account, but also the imagination of the future and the dream about the desirable scenario shape the ways of looking at the present. Also in this case the simulation has a role in supporting this back-and-forth dynamics between present and future and vice versa. Indeed, starting from initial (present) conditions and certain values of parameters the possible (future) scenarios are obtained. Then, elaborating on the scenarios, we arrive to the preferred one and at this point from this scenario (future) one goes back to the starting point of the simulation (present) to see how the parameters need to be changed. For this back-and-forth movement that embeds, this dynamical skill allows to overcome a linear, classical idea of time according to which the future can be obtained simply "extending" the present up to a certain moment.

<u>(Dyn3) Move from thinking at the individual to thinking at the societal community and/or the other stakeholders</u>

Reasoning about problems related to most future-oriented issues it is important to recognize the role of the individuals in the bigger picture of the societal community. This was very effectively captured by the students who, using agent-based simulations, could appreciate the role of the individuals and the interactions among them to create a certain scenario. Most groups talked about the role of the agents to create a problem but also underlined their potential in providing solutions. However, they realized that an agent is never isolated, and its actions can impact the whole society if there are others who support this initiative, establishing for example alliances between different stakeholders.

<u>(Dyn4) Think creatively for imagining new possibilities and concrete actions</u>

The creativity of imagining innovative solutions has been always considered a precious competence to be fostered through education. With this skill, the novelty of the ideas proposed by the students is emphasized. It is important to notice that the creative thinking that we want to reach is not an issue of absolute novelty with respect to the state of the art of the knowledge related to the issue considered. This would be totally beyond the reach of students working on a few hours' activity. On the opposite, this competence needs to be evaluated with respect to the novelty perceived by the students with respect to the idea they have had. Indeed, the innovation is not a matter of result achieved but of way of thinking to get there.

(Dyn5) Balance the need of aspiring and desiring with that of keeping feet on the ground

If dreaming about a desirable scenario is an imaginative activity which can be just connected to the sphere of desires, without necessarily thinking at practical constraints, the back-casting phase requires to construct backwards the story – made of actions, decisions, and contingencies – which has led to that future. Imagining this story requires to evaluate the role of the possible stakeholders, both positive and negative, considering also those whose interests clashed with the realization of the desirable future. Even if they are a minority, some groups succeeded in doing that, envisioning the conflicts that can arise or the practical constraints that cannot be ignored, and also taking them into account to shape the final desirable scenario, where dreams are balanced by opposite tensions.

(Dyn6) Think in a multidisciplinary way, breaking down the barriers among disciplines

The problems chosen by the students were difficultly framed within a single disciplinary field, as many future-oriented scientific issues are. Some students recognized that different disciplines contributed to their analysis of the problem. In particular, the simulation is a tool which embeds a variety of languages, and the students were surprised recognizing that so many disciplines could be involved. As a student told at the end of the course about her experience in the future-oriented activity: "I liked it [the activity] a lot because we found ourselves making reasonings that didn't even seem related to physics. One takes a problem that is not physical, because it is not physics in terms of numbers and equations and formulas. But then you try to take a general problem, which seemed to us almost to be talking about philosophy when we did this work, and then try to put it in a kind of table and then schematize everything with a model".

(Dyn7) Move from thinking in terms of necessity to thinking in terms of multiple possibilities

We have seen that the second dynamical skill regards the back-and-forth relationship between the present and the future. With the last future-scaffolding skill we remark the nature of this relationship that, far from being fixed and deterministic, contemplates a range of possibilities and gives to the future a plural form. Having asked the students to imagine at least three different scenarios was a way to make them aware of this plurality of futures that can be imagined. This was particularly easy with the future-oriented activity based on simulations because these tools allow to see very clearly that changing the parameters and the initial conditions the evolution of the system changes as well, but also that even with the same choice of parameters different futures can be obtained due to the complexity of the system.

As we did with the structural skills, we can look at the seven dynamical ones to grasp a bird-eye view on them. Just from their formulation, they are all skills that include a movement between opposites: from local to global (Dyn1), from present to future (Dyn2), from individual to society (Dyn3), from already explored solutions to new creative ideas (Dyn4), from a desired detached from reality to a dream that is grounded there (Dyn5), from one discipline to another (Dyn6), from determinism to a range of possibilities (Dyn7). The recognition of a tension between two or more points is what makes accessible the scaffold built with the structural skills. The steps of the scaffold, and the joints between different levels are metaphorically the basis for the navigation of the complexity of the future-oriented issues.

11.Conclusions

In this chapter we aimed at investigating the potential of the module in fostering the development and the put into action of future-scaffolding skills. Grounded on the research basis of the literature in future-oriented science education, we presented the analysis of rich data sets made of students' presentations and individual interviews. The first set of data allowed us to identify which structural and dynamical skills were put into play by the students in the analysis of a complex topic through computational agent-based simulations. The data set made of the video-recordings of eight individual interviews was used instead to check if the students were able to express and verbalize the development of these competences.
The analysis of groups' presentation clearly showed how the groups were very different for what concerns the structural and dynamical skills put into play in the presentation. However, the overall trend was that structural skills were more frequently detected than dynamical ones. This is an unexpected finding since it was the first time that this trend was observed as a result of a future-oriented activity. In our findings, the high frequency of structural skills confirms the importance of the scaffolding provided by a purposefully designed activity to trigger them. Indeed, as we argued in the discussion section, the very same structure of the activity invited the students to structure their thinking about the future-oriented issue in terms, for example, of distinguishing between problems, causes, goals, solutions, actions.
The analysis of the interviews allowed us to point out if the students were able to actively recognize the competences they had developed and to verbalize them. While performing this analysis, we realized that the students also talked, more naturally, about how their perception of the future changed throughout the module as the result of a process of widening and approaching. From the interviews, we obtained that on average dynamical skills and widening are the more represented macro-categories, while structural skills and approaching are the less frequent.
The most interesting result regards the comparison between the skills put into action and detected in the groups' presentations and those skills verbalized by the students in the interviews. As we said, in the presentations were detected much more structural than dynamical skills, while in the interviews the students gave slightly more emphasis to the development of dynamical than of structural skills. Indeed, the tailor-made designed activities of our module led the students to develop structural skills and put them into play when they have to scaffold their thoughts about a problem. However, when we ask them to describe these competences, the students seem to lack words to describe the achievement of these skills. This difference between the distribution of the two types of future-scaffolding skills deserves further analysis and that science education will need to investigate ways to make the students active protagonists of their own learning, able to recognize the huge, transversal gains they can have from science learning.

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Part study 1 - Agent-based simulations as models for thinking at societal issues

1. Introduction

In the first part study, based on the work by Fabbri (2021), we investigate the module's potential in making students use given models and simulations to address a range of diverse real-world phenomena. In particular, we focus on the fourth lesson of the module in which an activity was conducted to guide the students to construct correspondences between the elements of three previously analyzed simulations (wolf-sheep predation, voting and cooperation) and real-world problems (disappearance of small enterprises in favor of big companies, formation of echo chambers and comparison between sustainable and unsustainable lifestyles toward climate change). As described in Chapter 7, the design of the activity has been inspired by the theory of coordination classes, and in particular by the concepts of span and alignment (Levrini & diSessa, 2008). During the activity, various data were collected, including questionnaires, video-recordings oral discussion, shared boards. In the analysis we will show: i) how the students constructed the correspondences between social problems and the constitutive elements of the given agent-based simulations; ii) how the task of finding those correspondences helped the students enlarging their range of possible real-life problems that can be tackled using the given agent-based simulations; iii) how the students described the transversal features that are common to all problems addressable through the three simulations and the specificity of each one.

2. Research Questions

The analysis was conducted to answer the following research questions:

RQ1. How the students trace social problems back to the constitutive elements (i.e. typology of agents, interaction mechanisms, parameters) of given agent-based simulations? Which limits of the established analogies do they recognize?

RQ2. Which issues that can be modeled through the three simulations presented do the students imagine? To which extent did the activity contribute to enlarge this span of issues?

RQ3. Among the span of imagined problems, which transversal characteristics typical of agent-based simulations of complex systems and differences in the respective interaction models do the students recognize?

3. Methodology of data analysis

The data analysis of this part study was articulated in three phases, each of them addressed to answer one of the over-mentioned research questions.

3.1. Analysis of the questionnaires

The first phase of the analysis considered the data obtained with the students' answers to the three questionnaires that aimed at outlining correspondences between the elements of the reference simulations and the given real-world problems. Concretely, the students' responses to the forms were exported in three Excel tables (one for each simulation-problem pair) and anonymized. On these data, we performed a bottom-up analysis in which, to each item of the questionnaire, was associated a "standardized" column, as schematized in Table 1. The idea was passing from the words of students to codes that were able to capture the specificity of the students' answers but also to give back a global and intelligible picture, until saturation had not been reached. The codes of the standardized column were then grouped into larger categories, reported in the "category" column. These categories are those that will be discussed in the presentation of results. To provide an example of the coding steps, we focus on the predation mechanism of the wolf-sheep predation simulation in the schema of Table 2. To clarify some answers written by the students, we considered the oral comments of the students after filling the questionnaire.

Table 1. Schema of the table for the analysis of questionnaires exemplified in the case of the wolf-sheep predation simulation.

Student ID	Wolves	Wolves STANDARDIZED	Wolves CATEGORY	Sheep	Sheep STANDARDIZED	Sheep CATEGORY	Grass	Grass STANDARDIZED	Grass CATEGORY	Predation mechanism	Predation mechanism STANDARDIZED	Predation mechanism CATEGORY
M?	…	…		…	…		…	…		…	…	
F?	…	…		…	…		…	…		…	…	
M?	…	…		…	…		…	…		…	…	

Table 2. Examples of the coding phases: from the words of students (2nd column) to the standardized codes (3rd column) and to the categories (4th column).

ID student	Predation mechanism	Predation mechanism STANDARDIZED	Predation mechanism CATEGORY
M32	Large companies that incorporate or cause small businesses to lose customers	Incorporation & Losing customers	Big incorporate small
M4	Monopolization of the large producers of the market	Monopolization	Big expand themselves
F31	"incorporate" small businesses to grow large companies	Incorporation	Big incorporate small

F15	large companies with their often more favorable or cheaper prices for the production of products steal customers from small businesses making them fail	Stealing customers	Big steal clients to small
M7	when a small company is about to fail it is incorporated by the multinational	Incorporation	Big incorporate small
M19	difference in income, expense and efficiency of production	Differences of efficiency	Differences in growth strategies, efficiency, expenses and gain
M30	where the big company passes, it eats	Eating	Big eat small
M20	significantly lower prices and more convenient services for the customer	Differences of efficiency	Differences in growth strategies, efficiency, expenses and gain
F21	increase in online purchases and decrease in purchases in stores	Differences of habits	Differences in growth strategies, efficiency, expenses and gain
M9	expansion of multinationals	Expansion	Big expand themselves

To answer the second part of the research question and understand whether the students recognized the limits of the analogy between the reference model and the real-world issue, we analyzed the students' answers to the last item of the protocol ("Other analogies or differences that you see between the simulation and the real problem"). The analysis of these answers followed the same methodological steps written above for the previous items of the questionnaires.

3.2. Analysis of the brainstorming activity on the shared board

To answer the second research question, the data taken into account were the items added by the students on the shared boards during the activity of imagination of problems' contexts during the first and third phase of the activity. Since we wanted to investigate if and how the activity enriched the students' imagination about the different contexts of problems, in a first phase we analyzed the responses obtained before the activity, and then we compared the responses obtained after the activity to those previously collected.

3.3. Analysis of the final discussion

To answer the third question, we considered the transcript of the final collective discussion, when students were requested to recognize in all the problems identified common features and differences. Since only five students took actively part in the discussion, the aim of this analytical phase is not to give a global picture of how the understanding of these issues were spread among the participants, but we considered the interventions of the students as the best results that could be achieved with such an activity.

4. Data analysis

4.1. Analysis of questionnaires on simulations and real problems

4.1.1. Wolf-sheep predation

The students who gave an answer to the questionnaire on the similarities between the wolves-sheep predation simulation and the real problem of the disappearance of small businesses in favor of the affirmation of large companies were 32. Two of them preferred not to indicate their names in the questionnaire so we do not have the reference to their identifier. We recall that the questionnaire started in this way: *Let's tackle the problem of the disappearance of small businesses in favor of large companies, franchising, online giants through the NetLogo "wolf sheep predation" simulation: what do the various elements of the simulation correspond to in the real problem?*

All the students but one established the correspondence that we expected for the types of agents: wolves were associated to the large companies, while sheep to small enterprises. They used different expressions to indicate it: for the wolves they use expressions like "big enterprises", "commerce giants", "big multinationals", for the sheep "small businesses", "small shops", "artisans", "little entrepreneurs", "small and medium-sized enterprises". We find the only exception in M6 who assigned to wolves the meaning of taxes and to the sheep the role of small and large entrepreneurs. After filling the questionnaire, the student explained his reasoning verbally:

> *When I did the questionnaire, I thought that perhaps it was not exactly right to consider wolves as multinationals. Because in the simulation the wolves feed on sheep and the multinationals don't feed on small businesses. Both should feed on grass. In fact, I attributed to the sheep the meaning of small and large entrepreneurs and the wolves, which affect the sheep, I imagined them as taxes. Consequently, there should be two types of sheep, one that can breed faster, keeping up with wolves (the big companies), while a type that tends to suffer taxes (the small businesses).* (M6)

In his explanation, M6 recognized the limit of the correspondence between wolves and big companies and between sheep and small enterprises. For him, what breaks the correspondence is that, while in the simulation the wolves eat sheep, here it is not accurate to say that big companies eat the small businesses. Instead, there is another element – the taxes – that eats both. Instead of seeing an asymmetry between big companies and small ones (the former predating the latter), he imagines that the differences should regard the kind of response that big and small companies have toward taxes. However, M6 is not considering that, if we give to them different response strategies, big and small companies should be distinguished and cannot be the same agent (in this case, the sheep).

The students' responses were more diversified for what concerns the meaning attributed to the grass and the predation mechanism. These responses are shown in the following graphs (Figure 1 and Figure 2).

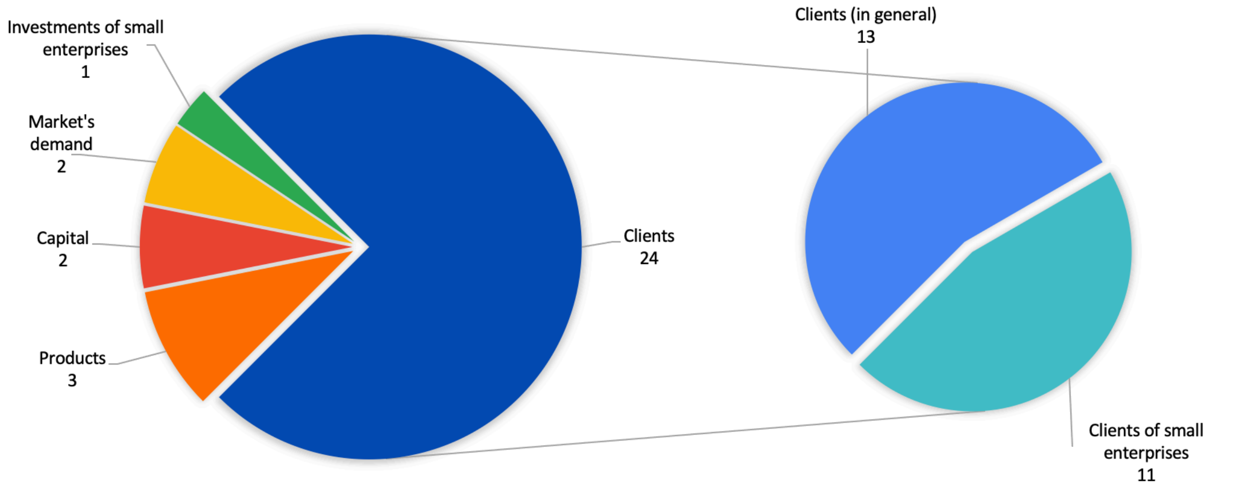

Figure 1. Meanings attributed by students to grass in the wolves-sheep predation simulation in the context of big-small enterprises dynamics (Total answers: 32).

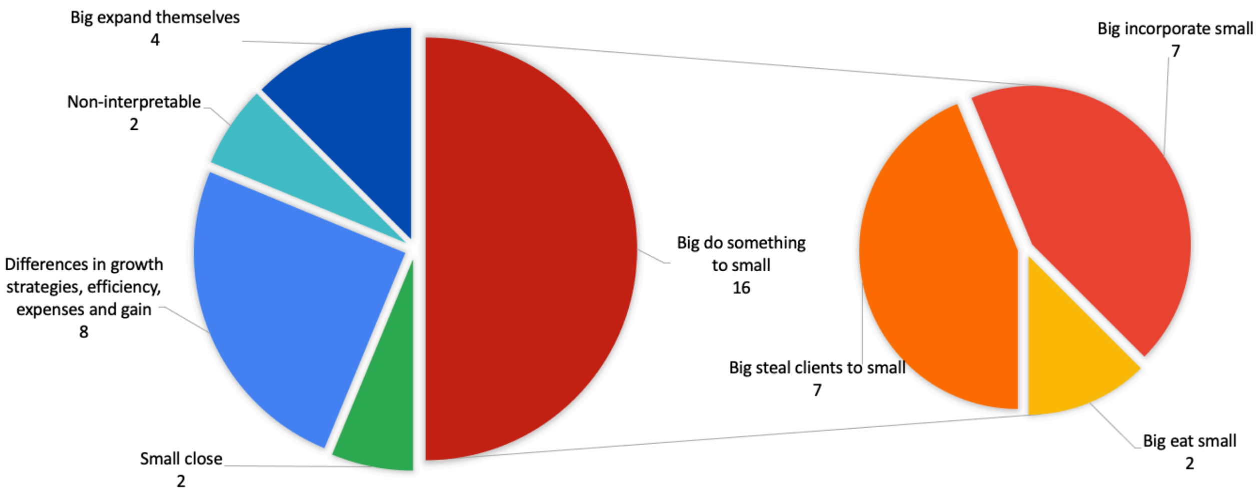

Figure 2. Meanings attributed by the students to the predation mechanism of the wolves-sheep predation simulation in the context of big-small enterprises dynamics (Total answers: 32).

As shown in the graph in Figure 1, most of the students attributed to the grass the meaning of customers (24 out of 32); about the half of them (11 out of 24) specified customers of the small businesses, in agreement with the *a priori* analysis of the questionnaires (indeed, in the reference model only the sheep eat grass, not the wolves). The other answers referred to the products sold by the enterprises, the request of the market, capitals, and investments. In general, all the answers provided by the students can be considered in line with what we expected. Their diversity highlights how the students thought at different nuances of the problem, but we can conclude that the students have grasped the main idea of grass as what makes enterprises grow. For the majority of students (20 out of 32), both big and small enterprises "feed" on their customers, while one third sticked to then reference model in which only sheep benefit directly from grass (the wolves benefiting from the sheep themselves).

In Figure 2 we observe the distribution of students' interpretations of predation mechanism in the real problem. Half of the student (16 out of 32) recognized in the problem involving big and small enterprises a dynamic that we can summarize as "big enterprises do something to small ones". These students describe the type of action of the big companies with different terms:

- big "incorporate" small enterprises (7 out of 16);
- big companies "steal customers" to the small businesses (7 out of 16);
- big businesses "eat" small ones (2 out of 16).

The third seems quite a literal interpretation of the predator-prey model. The eating/feeding dynamic that exists in the simulation is automatically transposed to the real-world domain, without specifying the actual correspondence. On the opposite, the ideas of incorporation and stealing customers reveal a further elaboration of the analogy, using new words to describe a phenomenon in a different domain than that of reference. However, we note that while the first of these answers is in line with what we expected from the *a priori* analysis, the second answer does not fully reflect the interaction between wolves and sheep in the simulation: wolves, in fact, do not steal grass to sheep but rather feed on the latter.

The other half of responses about the predation mechanism are varied. 6 of them focus only on one type of agent and tell what happens to them: small businesses end up closing (2 students) or large companies expand themselves (4 students). We highlight that, even if these could be interpreted at first-sight in a similar way to the previous answers on incorporation, stealing and eating, there is an outstanding difference: saying that small businesses end up closing gives only a static picture of a situation, the final result, without entering the reasoning on the causes that have led to that; on the opposite, the previous examples concerned an actual interaction between big and small enterprises that leads to the observed result. Coming back to the reference model, the difference between the two types of action is similar to the difference that exists in saying "sheep die" and "wolves eat sheep and sheep die".

Finally, 8 students saw the correspondence with the predation mechanism in specific differences that characterizes the market strategies of the two types of enterprises. In this case, the students seem to refer to economical differences in the model of business but the way in which big and small companies interact is not made explicit. Examples of students answers for this category are:

> *Difference in income, expenses and production efficiency (M19)*
>
> *Significantly lower prices and more convenient services for the customer (M20)*
>
> *When large companies meet small businesses on the market, the former take the profit, while the latter do not cash in (F17)*
>
> *Use of advertising to attract customers (F34)*

It seems that with their answers these students are actually trying to characterize more the difference between the types of agents rather than the way in which they interact.

In the end of the questionnaire, the students had some space to leave further similarities or difference that they saw between the problem and the simulation model. For what concerns the analogies, one student writes a comment about the overall pattern of time evolution of the two agents' populations:

Among the analogies we can see how exactly as when wolves increase and sheep decrease in the same way, when large companies start to make room, small shops struggle (M18)

For this student, the analogy can be completed by looking at the macroscopic behavior of the groups of students and the temporal evolution of the groups' sizes.
More students pointed out some limits of the analogy between the reference model and simulation and the real-life problem. Few students question the feasibility of using a simple model to describe this problem. Indeed, the real-world issue at stake is more complicated and there can be adaptation chances that are not included in the model:

I notice that small businesses have non-simulable adaptation possibilities. (M33)

Another difference is recognized at the level of local rules of interaction and regards again the concept of grass which in the model is food only of sheep and not of predators, while if we consider grass as customers, big companies also feed on them:

In reality the wolves would "steal" the food from the sheep (M29)

Other students identified limits of the analogy in the global time evolution that the number of big and small enterprises exhibit:

With regard to the differences, we can see that there is no tendency to reach equilibrium unless other external parameters influence the experiment from time to time favoring one and the other alternately. (M18)

Once the sheep are defeated, the wolves begin to feed on each other, letting only the strongest survive. (M19)

The biggest difference should be in the fact that large companies tend not to multiply exponentially like wolves in number, but in extension, this expansion should be quantified, so that a single large company can occupy a greater basin of market demand. (M8)

4.1.2. Voting

The students who answered the questionnaire regarding the similarities between the voting simulation and the real problem of echo chambers on social networks were 27, and two of them preferred not to indicate their names. We recall that the questionnaire started in this way: *Let's face the problem related to the fact that, on social networks, we are exposed to news and information that reinforce our opinions (phenomenon of "echo chambers"): what do the various elements of the simulation correspond to in the real problem?*
All the students attributed to the green agents and the blue agents of the simulation the meaning of conflicting information, news or opinions. They unanimously contraposed a group of people who share an opinion against a group of people who share another opinion, or opinion 1 against opinion 2, or pieces of information in line with our beliefs or pieces of information against our beliefs, or again fake news against authentic news.

About the meaning of the agent's neighbors, the answers were more diversified as Figure 3 shows.

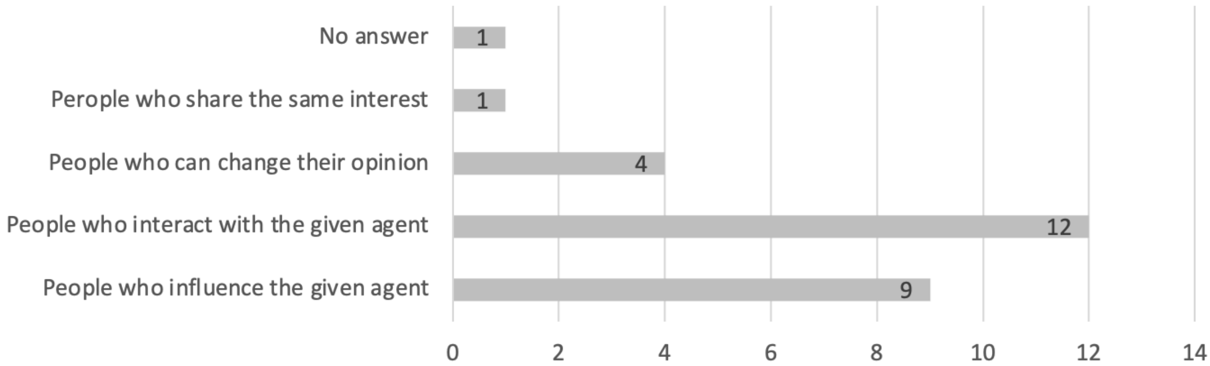

Figure 3. Meanings attributed by students to the neighbors of an agent in the voter simulation in the context of the formation of echo chambers (Total answers: 27).

12 students attributed the expected meaning of people interacting with a user, for example through a social network:

Ideas of the people with whom we are in contact through the use of social networks (anonymous)

Opinions of people around you (F31)

People [who appear to us] in [the Instagram] feed (M35)

People with whom I discuss on social networks (F14)

One student identified the neighbors as those who share the same hobby or interest. Even if this is similar to the previous category, in this case there is no reference to the interaction between agent and its neighbors but only to their "vicinity".
Another much populated category is that of students who recognized in the neighbors the people who can influence the given agent:

People whose opinion is known (M13)

Pages / content creator (M33)

Other people who influence thinking (M4)

Friends, relatives, but also influencers (M6)

This is certainly true, but the ways in which the students formulate their answers (for example, referring to influencers or sources of information or to the fact that the neighbors have an already known opinion) make us think that the influence that the students are imagining is unidirectional. On the opposite, in the voter model, each agent is influenced by the surrounding ones but, conversely, can also change its neighbors' opinion.

The last meaning assigned by the students were those of undecided users, whose opinion is not precisely defined yet (4 out of 27):

People who have approached both positions and are undecided (M18)

Individuals who are searching for information (M29)

People for whom the social algorithm has to decide whether to give them advertisements with a pro or con position with respect to opinion A (M32)

The answers given by the students to the two variants of the voter model, named "change-vote-if-tied" and “award-close-calls-to-loser”, have been grouped in categories and reported respectively in Figures 4 and 5. We briefly recall that in the “change-vote-if-tied” variant, in case of a 4-4 between the surrounding opinions, the central agent change its opinion, while in the “award-close-calls-to-loser” variant, in case of a 5-3 situation, the central agent takes the opinion of the minority.

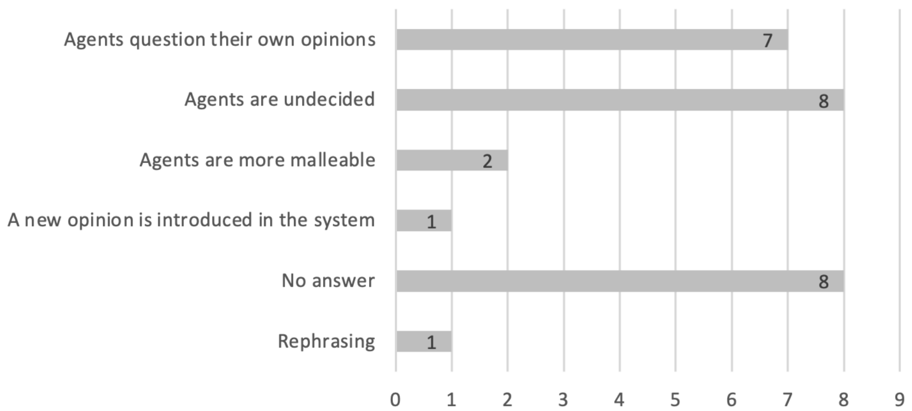

Figure 4. Meanings attributed by the students to the “change-vote-if-tied” parameter of the voting simulation in the context of the formation of echo chambers (Total answers: 27).

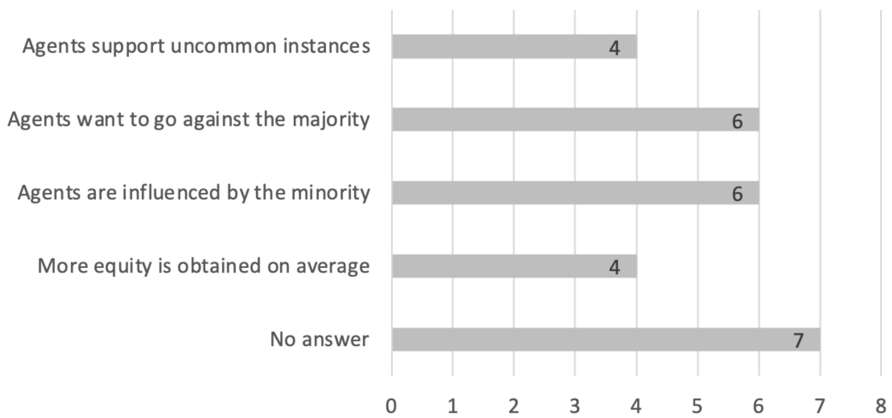

Figure 5. Meanings attributed by the students to the “award-close-calls-to-loser” parameter of the voting simulation in the context of the formation of echo chambers (Total answers: 27).

In both cases we notice that a considerable number of students (9 students out of 27 in the first case and 7 out of 27 in the second one) did not provide an answer or limit themselves to rephrasing the question.

Regarding the first variant, with which the agent changes its opinion in case of a draw between the neighbors, we have four main interpretations. The majority of students (15 out of the 18 who provided an answer) wrote that this new rule represents agents who question their own opinion or that are undecided and more willing to change their beliefs. Other ideas (chosen by 3 students out of 18) regard the fact that with this variant the agents are more malleable or that a new opinion is introduced in the system so as to mediate between the two contrasting ones; however, these interpretations do not find any correspondence with the variant implemented in the voting simulation.

For the second variant, where in case of a 3-5 situation the central agent takes the opinion of the minority, 16 students out of the 20 who answered the question state that the agents support uncommon instances (4 students), or go against the majority (6 students), or are influenced by the minority (6 students):

> *I change my opinion even if those I have talked on social networks are in a higher number of my same opinion and fewer with the opposite one. (F14)*

The remaining 4 students, instead of thinking at a change in the rules that describe the change of opinion, focus on the overall result of the application of this variant on the system.

> *The algorithm that tries to maintain a fair alignment between those who are in favor and those who are against an opinion. (M32)*

This answer is particularly interesting since it seems to reflect the difficulty, well-explored in the literature on the teaching of complex systems, in understanding the self-organization characteristic of a system in favor, instead, of the explanations that assume the existence of centralized control. In this case the “algorithm” since to play the role of the centralized engine that makes the system evolve accordingly on a macroscopic scale. However, this remains a quite isolated attitude in the data collected and addressed in this part study. For example, after the students had filled the questionnaire, they were asked what makes it possible to move from the initial random distribution of opinions to the final configuration with blocks of shared opinions. An interesting answer was given by a student:

> *In my opinion, in the real case this is due to disinformation. If the agents could move there would be a confrontation that would lead to the rising of new opinions. (F17)*

This student highlighted a fundamental property of the simulation taken into consideration: the mechanism of change of opinion is not influenced by the global system, but rather by the local vision of each agent on the system, which changes opinion according to those around it.

As we did with the predation simulation, also for the voting we asked a final comment to the students about further analogies they saw and about differences that constitute the limitations of the analogy itself. Three students identified some limitations with respect to the analogy being outlined. They reflect on the fact that the simulation describes only partially the complexity of the social networks dynamic. For one student the simulation is not reliable since on social network not all information is accessible, but it is "filtered", while the simulation does not seem to reflect this:

> *On social media you can search for what you claim and often the info is filtered, so you cannot fully refer to the simulation. (M33)*

Another student underlines the fact that in real settings there is an individual variability which is not captured by the simulation in which all agents behave according to the same rules:

> *[…] for what concerns the differences we can see how not everyone constantly changes their opinion and some do not let themselves be influenced by others. (M18)*

Finally, a student recognizes that often there are more than two opinions for the agents to choose:

> *It is difficult to apply to reality as there are not only two opinions, however it can be applied to cases such as US elections where votes mostly fall on only two candidates. (M19)*

4.1.3. Cooperation

The students who answered the questionnaire on the similarities between the cooperation simulation and the ecological problem were 28, and one preferred not to indicate his/her name. We recall that the questionnaire started as follows: *Let's face the problem related to the fact that, in the light of the climate emergency, lifestyles more or less ecologically oriented can be adopted: what do the various elements of the simulation correspond to in the real problem?*

All the students attributed to the agents of the simulation – the greedy cooperative cows – the meaning, respectively, of people disinterested in the ecological problem ("those who do not adopt eco-oriented lifestyles", "consumers who are not aware of their impact", "people who pollute a lot") and people sensitive to the environmental issue ("those who adopt sustainable lifestyles", "conscious consumers", "people who pollute a little").

The results obtained for the meaning attributed to grass and to the mechanism of grass' consumption are more varied as reported in Figure 6. Most of the students have attributed to grass the meaning of natural resources (18 out of 28) and some of them made more explicit that only non-renewable resources count as grass. The remaining students considers the grass as the environment in general, or refer to pollution factors, or the time left for the humanity to find solutions to the climate emergency.

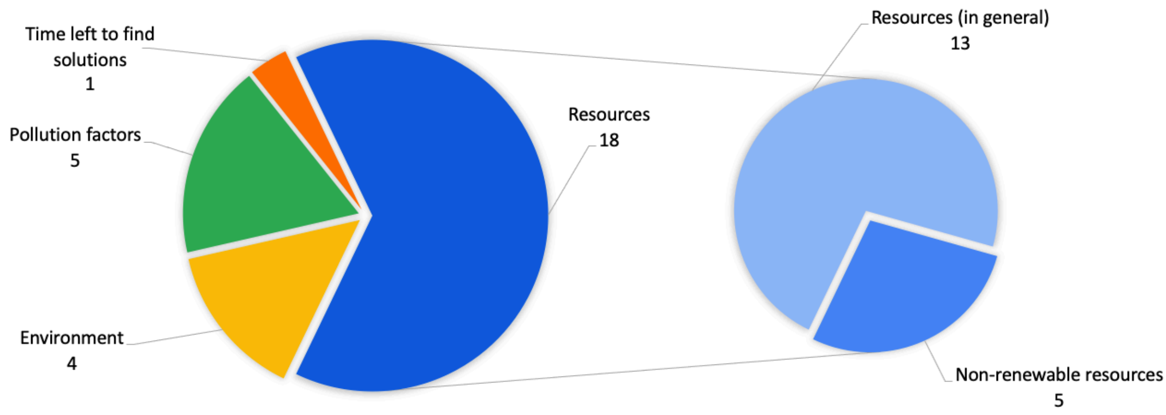

Figure 6. Meanings attributed by students to the grass in the cooperation simulation within the context of the contrasting lifestyles (Total answers: 28).

For what concerns the mechanism of grass consumption – the responses are reported in the graph in Figure 7 – half of students interpreted the consumption of grass as the consumption of resources, while the others talked about different forms of environmental impact.

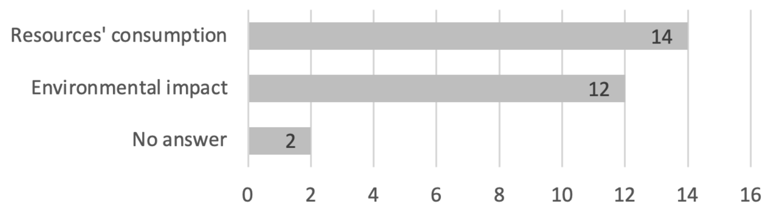

Figure 7. Meanings attributed by students to the mechanism of grass' consumption in the cooperation simulation within the context of the contrasting lifestyles (Total answers: 28).

The responses to this item of the questionnaire are clearly strictly related with those of the previous question about the meaning of grass. Most of the students who attributed to grass the meaning of resources, then attributed to the consumption of grass the meaning of their use. Other students who had instead focused on the problem of producing energy from various sources (renewable and non), assigned to the consumption of grass the meaning of production of energy. Finally, other students who had attributed the generic meaning of environment to grass, here considered its consumption as a form of negative environmental impact, such as air pollution in a city.
This is reflected also by the contraposed modalities of grass' consumption: the greedy and the cooperative ones. Some examples of the opposite pairs from students' answers were:

Ignoring waste sorting / Trying to recycle as much as possible (M33)

Use of non-renewable energy and polluting resources without limits / Use of renewable energy and sustainable lifestyle with low environmental impact (F21)

People who do not make ecological choices will tend to consume non-renewable energy sources faster / Ecologists exploit renewable forms of energy that have low impact on the environment and allow less consumption of non-renewable ones (M8)

They use the car every time they have to move / They use the car only if it is necessary (F14)

At the end of the questionnaire, as we did for the previous two, we asked the students to highlight further similarities or differences that they recognized between the model-problem and the real-world one. A student, thinking about a limitation of the analogy, writes the following sentence:

Ecologists consume less not because they collaborate with each other but because they exploit renewable forms of energy that reduce the environmental impact of life and therefore the consumption of "grass" (M28)

It is particularly interesting since he seems to assign the everyday use of the "cooperation" term to what is actually modelled in the reference simulation. Indeed, not even in the model there is an actual collaboration between the ecologists: cooperation is rather a sort of emergent behavior that results from the implementation of concrete sustainable actions, as the student is saying.

4.2. Analysis of the real problems proposed by the students

To understand if the students were able to imagine new contexts that could be modeled through the three simulations proposed, we analyzed the answers provided through the shared board during phase 1 and phase 3 of the activity. In particular, by comparing the answers provided before and after, we were able to understand if and how the activity had helped the students to enlarge the span of contexts in which these simulations were applicable. The answers provided by the students during these two phases are reported in table 3.
Observing the table, we notice that during the preliminary brainstorming, it emerges rather a narrow span of problems that the students think can be modelled with the simulations they have been presented. The most evident case is that of the wolf-sheep predation. In the beginning, all initial answers referred to the biological sphere and competition between species, while after the activity the problems imagined were much more diversified. Having seen an example of predation outside the biological context, with the case of the competition between large companies and small enterprises, the students found a way to enlarge their span of possible application contexts of the same model. For example, they imagine a situation in which innovative initiatives try to challenge established ones, or cultural dynamics in a sexist society.
For what concerns the voting simulation, since the beginning the students imagined a variety of possible related problems or contexts which all share an idea of influence. In particular this influence goes from the cultural dimension ("Construction of social rules and opinions shared by a community") to market dynamics ("The distribution of brands linked to social or fashion status"), passing through biological phenomena ("Studying the spread of a virus").

Table 3. Result of the brainstorming activity on real-world problems that can be modeled through the simulations before and after the work on the three analogies.

	Wolves-sheep predation	Voting	Cooperation
Before	- Extinction of an endangered species - Extinction of animals - Excessive increase in the population of predators within an environment - Overpopulation - With an appropriate change, study the competition between subspecies - Growth of a population of bacteria on a slide in which their predatory agents (antibodies or viruses) are also present - Understanding when an animal's hunting season can be opened and how long it should last - Secure animals at risk	- How influential prejudices can be - The distribution of brands linked to social or fashion status - Construction of social rules and opinions shared by a community - Try to take courses to make young people especially aware of important issues such as bullying - Studying the spread of a virus - How can the choices for the university be influenced - Public opinion	- Analyzing how to favor the emergence of different social behaviors and understanding how realistically it is possible to eliminate the worst or having to be content with limiting their spread - Having to weigh the resources available, drinking water for example - Improve the place where you live by trying to do something in his own small way - Relationship between the common good and the interest of each individual - Organization and coexistence within a community - In a business situation, thinking only of your own work could harm that of others - State ecological management - Industrial sustainability at company level
After	- How traumas or even beliefs can be harmful to a population - Simulate bivalent chemical reactions between two products - The birth of new initiatives that go against those already present - Types of emotions that collide between two subjects, the wolf subject who is temperamentally aggressive and the sheep subject who is docile - Victim / aggressor dichotomy - Dynamics within an environment in which the woman is seen as an object - Distribution of wealth between primary activities and cultural transformation / mediation / production activities	- The birth of clubs (such as those for pregnant women or for reading enthusiasts), only those who have a common interest enter here - Elections in countries where there are only two main candidates (such as the United States, for example) and where people are so convinced of their choice that they consult exclusively with people of their own faction, ignoring the opposition - Creation of groups within a classroom - Appreciation of a work (videogame, cinematographic, editorial, etc...) by a community or by the general public	- Lifestyle difference between rich and poor - Respect the laws that are given to us for a common good, such as compliance with the rules against contagion, in the hope of avoiding the continuing epidemic - Simulate the development of a project, distinguishing between self-employed and team workers (the grass parameter should be changed)

4.3. Analysis of the final guided discussion

In conclusion, we analyzed the reflections and reasonings reported orally by the students during the last phase of the activity. Indeed, we want to check, after the guided construction of the analogies, if the students are able to recognize in different application contexts the transversal characteristics typical of agent simulations of complex systems and their differences in their respective interaction models. In this case, what the students were expected to do was a process of guided "alignment", following the lexicon of the theory of coordination classes. We recall that the discussion was guided by the following questions: *What do the problems described by a specific simulation (wolves-sheep predation, voting or cooperation) have in common? What distinguishes them from those that can be represented with the other simulations? What are the interaction mechanics embedded in the problems identified?*

In the discussion, only five students participated, so we cannot give a global picture of how the understanding of these issues were spread among the participants. In some sense, we consider the interventions of the students as the best results that could be achieved with such an activity.

The first response of a student to the questions posed during the fourth phase of the activity is shown below:

> *All the models are based on the interactions between agents. However, in the first simulation (wolves-sheep predation) the interaction between agents is based on fixed laws (the wolf always eats the sheep) and therefore when there is an interaction we know already what its result will be. In the voting simulation the agents are equal and their interaction changes, there is a different result for each interaction that changes according to the color of the neighboring agents. For the cooperation simulation the two types of agents do not interact with each other but rather with the surrounding environment, the interaction between the two individuals is due to the interaction with the environment, as if this were a third agent. (M8)*

With this answer, the student highlighted the main characteristic common to the three simulations, that is, the interaction between the agents. However, he also underlined the differences between the ways in which these interactions are modelled.

The predation and cooperation simulations embed an element of competition between two species, but with the predation model the competition is direct (one species feeding on the other) while in the cooperation simulation the competition is mediated by the consumption of the same resources ("the two types of agents do not interact with each other but rather with the surrounding environment"). This point allowed to focus the crucial distinction between the predation and cooperation simulations, beyond the similarity of the simulation's surface that in both cases concerns the animal kingdom. In this sense, M8 clarifies one point that another student leaves more implicit:

> *The first and third simulations could be united by the dominance of one agent over another. (M25)*

Indeed, while M25 only identifies the similarity between the predation and cooperation simulations, M8 succeeds also highlighting the differences.

Another level of difference that M8 identifies regards the characteristics of the agents. In the predation and cooperation simulations the main feature of the agents is in some sense "intrinsic" to them – this determining the fixed rules of their interaction. On the opposite, in the voter model the agents are mainly described by their opinion, an "extrinsic" property – which is variable and change as a result of the interaction with the neighbors. For the student, this difference in the ways of characterizing the agents is of outstanding importance because it impacts the way in which the interactions are saw: in one case they are fixed and produce expected results ("when there is an interaction we know already what its result will be"), in the other the results depend on the opinion-value that each agent has in a given moment ("the agents are equal and their interaction changes, there is a different result for each interaction that changes according to the color of the neighboring agents").

An additional layer of comparison between models is introduced by another student:

> *I think that what unites the three simulations are the relationships that exist between the elements, their connections. What differentiates them, however, is how much these elements affect others and how much these elements impact the context itself. For example, the first simulation [wolves-sheep predation] had two elements that influenced each other, and they were both cause and context; in the second simulation [voting], however, the single person is influenced by the multiplicity of other people who create the context and, finally, in the third [cooperation] all the elements are confronted with the context that changes according to them. (M4)*

He reflects on how the different models proposed distinguish "causes" and "context". In the predation case the two agents (wolves and sheep) are both cause and contexts, in the voting, each agent considered central is influenced by its context which is made by the neighbors, and in the cooperation the two kinds of agents interact separately with the context (the resources) that changes as a result of the agents' actions on it. However, in this explanation the student seems to neglect the role of circular causality which is embedded in these systems. Indeed, distinguishing so sharply the agents (those who *cause* the changes) and the context (what is *affected* by the actions of the agents) hides the complexity of the feedback mechanisms. Even if it is true that, for a single iteration in a single tick of the simulation, cause and context can be identified clearly, this is false in general since the action of an agent changes the context which in turn determines the following actions or features of the agent and so on. This point is grasped by another student who makes a reflection on the type of causality that occurs within the simulations of complex systems, in particular in the cooperation one:

> *There is a difference between the first two and the last. The interaction between agents in the first two simulations is direct. In fact, the interactions between agents directly influence others, while in the last simulation the influence a person has on others is indirect. Your choices in fact affect the environment and therefore the environment affects the other agents. While for the other simulations it is the agent himself who acts on the other agents, whether it is to change his mind or to eliminate them. (M19)*

In this last comment, the student recognized the non-linear causality and the phenomenon of feedback which is typical of complex systems: even if there is no direct interaction between the two selfish and cooperative agents of the cooperation simulation, they influence each other anyway.

The last comment was made by a student who reflected on how the combination of the three simulations can be productive to model a specific problem:

> *In the wolf-sheep predation, we notice how a movement… we can think of the traditional movement of thought that sometimes extinguishes the evolution or progress that exists in this period. One can think of sticking to one's routine because is scared of progress... and therefore it is as if one were almost himself the wolf and the sheep at the same time, as if he were killing himself while standing still. On the other hand, cooperation, if it were possible to push everyone towards evolution by noticing what the positive characteristics are, or that a group is able in such a profound way to try to carry on progress, so that despite the fact that there are those who are still anchored to the past and their traditions cannot be erased from this process... and this can be done with voting. If one influences others, it still manages to lead to progress. If you combine these three types of simulations it can lead to the efficiency of a purpose... I am talking about progress because it is something that interests me particularly but any idea that one wants to put into practice and act for this idea, if you use these three fields you could probably get to your goal. (F15)*

The students, at the end of the activity, were therefore able to recognize in the variety of imagined problems transversal characteristics typical of agent simulations of complex systems and the differences in the respective interaction models; moreover, the answers provided by the students during the guided discussion are characterized by a great plurality and a multiplicity of perspectives and levels of analysis.

5. Discussion and conclusions

In this first part study we have analyzed how the students progressed during the activity on the construction of analogies between the problems modelled in NetLogo simulations and real-life issues. This activity, inspired by the theoretical learning model of the coordination classes and structured in four main phases, was aimed to guide the students of the course in the construction of their “coordination class” for the mechanisms underlying the simulations of complex systems, and, more specifically, for the three agent-based simulations illustrated during the laboratory. In particular, the activity led the participants to, firstly, create a shared span for and, then, to find an alignment across the multiplicity of contexts.

Indeed, during the third phase of the activity, the students were able to extend the mechanisms underlying the simulations presented to areas and application contexts they had not thought of at the end of the theoretical explanation of the three simulations alone. Therefore, we can conclude that the activity of guided construction of the correspondence between the elements of the simulation and the real problem was effective in helping students to overcome the so-called “span problem”.

Moreover, during the last phase of the activity, some students were able, through a guided discussion, to recognize in the various imagined application contexts the transversal characteristics typical of agent simulations of complex systems and their differences in their respective interaction models. The students who spoke during the discussion recognized the main common feature of the three simulations in the interaction between the agents and identified the differences between the various application contexts in the way these interactions occur. They were also able to recognize in the specific simulations general characteristics typical of complex systems such as non-linear causality and feedback phenomena that exist among the levels of the system and its components. The activity has therefore proved effective in helping students to overcome the problem of alignment.

6. References

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Part study 2 - Simulations to construct scenarios of equilibrium for complex societal issues

1. Introduction

In the second part study we investigate one of the main features of the scenarios obtained by the students in the future-oriented activity which is the idea of equilibrium. The analysis of the data collected during the course for secondary school students was based on the results of a preliminary study carried out in 2020 with university Physics and Mathematics students, in which a similar future-oriented activity was proposed to the students (Barelli & Levrini, 2021). In that study we investigated the ways in which the students used the simulations in the future-oriented activity and the strategies they put into play to construct their future scenarios on the basis of simple simulative tools like NetLogo simulations. Even if that study allowed to point out some possible ways for the students to analyze problems basing on simulations, to build scenarios and plan actions, the lack of reflection on the mechanism of agents' interaction made it difficult to produce reliable desirable scenarios. From here we started with the analysis of the students' presentations at the end of the course on simulations of complex systems and analyzed how the concept of dynamical equilibrium made the students obtain more articulated and reliable scenarios.

2. Research background: the study with university students

The analysis conducted on this part study is based on the results of a study conducted with university students (Barelli & Levrini, 2021) and profoundly inspired the design of the course which is object of this chapter.

2.1. The activity

The future-oriented activity of scenario building was carried out for the first time as part of an 8-hours module which was designed and implemented in December 2020, through the Microsoft Teams platform. The participants were 60 university Physics and Mathematics students, enrolled in a course on Physics Education. The module comprised a two-hours lecture about simulations and complex systems, a central part (four hours) with group activity and two final hours were devoted to groups' presentations and collective discussion. For the group activity, the students were divided in 9 groups to work on a given task. After having explored some models available in the NetLogo Models Library (Wilensky, 1999), the members of each group had to choose a simulation that, in their opinion, concerned a problematic issue in the present. Using the simulation, they had to outline different possible future scenarios and one desirable scenario in which the problematic present issue had been solved. The final step required an operation of action planning: starting from the description of the ideal scenario, the students had to imagine which actions, policies or decisions made that future possible.

2.2. Methodology and research questions

The study had been conducted to understand the potential of NetLogo "toy" simulations as basis for scenario building and future thinking. Specifically, we addressed the following research questions:

RQ1. In which ways did the students use the simulations in the future-oriented activity?

RQ2. In particular, which strategies did the students put into play to construct their future scenarios on the basis of simple simulative tools like NetLogo "toy" simulations?

To answer these questions, the students' discussions in the groups as well as their final presentations have been video-recorded and analyzed. The analytical process used qualitative methods inspired by grounded theory (Glaser & Strauss, 1967) with explicit back and forth dynamics, from bottom-up data exploration to their theory-oriented interpretation (Anfara, Brown & Mangione, 2002).

2.3. Data analysis and results

The NetLogo simulations chosen by the students were used across all three phases of the future-oriented activities: analysis of the problem, scenario building and action planning.
About the analysis of the problem, the simulation served in some cases as the inspiration to identify a real problem of interest (e.g. the exploration of a simulation on altruism led the students to address the distribution of ecological attitudes in the population) and in other cases as a model in which the students recognized some features of a problem they had already decided to study (e.g. deciding to address the problem of COVID-19 diffusion made the students choose the simulation for HIV transmission).
The scenario building was the part of the future-oriented activity in which the students used the simulations the most. In particular, four main strategies have been identified to describe how the groups of students used and worked on the simulations: i) adjusting the parameters of the simulation to obtain the possible behaviors of the system and the optimal configuration that produces the desirable scenario; ii) questioning the assumptions behind the model to obtain different scenarios than those produced by the simulation; iii) modifying the rules of the simulation and implementing them in a new simulation; iv) extracting from the simulation the model of agents' interaction and transposing it to another domain. The first is a typical trial-and-error strategy, where the students interact with the simulation as a "black box": they change the value of parameters and evaluate the outcomes produced, but the mechanism underlying the simulation remains opaque. On the opposite, the focus on the mechanistic dimension characterizes the other three strategies: in the second one the students qualitatively reason on the model's assumptions; in the third one the mechanism is enriched at the coding level; in the fourth one the mechanism of agents' interactions becomes the basis for mapping the model's features on the new target system.
The different strategies for scenario building impacted the ways in which the students addressed the task about action planning. For example, some groups worked directly on the simulations and,

after having individuated the combination of parameters leading to the desirable simulated scenario, interpreted these values as a certain policy to be implemented. A different approach was chosen by the groups who had elaborated on the model behind the simulation, changing the assumptions or modifying the rules: in these cases, the students did not rely directly on the given simulation but planned the actions in contrast to what the simulation displayed. In general, the strategies of scenarios building which were grounded in the mechanistic level of interaction were more effective in the action planning phase.

2.4. Discussion and conclusion

The strategies used by the students were particularly useful for dealing with NetLogo "toy" simulations. Indeed, most groups recognized that, for obtaining reasonable scenarios, they had to abstract, in some way, from the simulation. This process of abstraction was essential for them to move from the extreme simplicity of the simulation to the comparison with real-world situations, without getting trapped in naïve epistemological ideas that want a model to be "realistic" to be trusted (Gilbert & Osborne, 2007). On the opposite, recognizing the limits of the models and engaging with the mechanistic dimension of the simulation (represented by the rules of agents' interactions), was a way for the students to increase their understanding of the model itself, arriving in some cases to propose original ideas. Finally, the study showed how the predictive power of simulations can be addressed in education and how, through specifically designed future-oriented activities, the simulations can become a laboratory to imagine possible and desirable scenarios for real-world systems.

3. Research questions

In this part study we address the following research questions:

- RQ1. How does the concept of equilibrium characterize the scenarios imagined by the groups during the future-oriented activity?
- RQ2. To which extent were the students aware of the peculiarity of this kind of reasoning?

4. Methodology of data analysis

To answer the first research questions, the video-recordings of groups' presentations were analyzed to find whether or not the equilibrium was part of the description of possible and desirable scenarios. To answer the second question, we analyzed the video-recording of the final collective discussion, when students were guided by the instructors to reason about the types of scenarios identified. In this way we checked whether the students were aware of the peculiarity of the scenarios of equilibrium to produce future reliable scenarios.

Before presenting the results of the analysis, centered on the concept of equilibrium, in the next section we provide a general description of the presentations made by the seven groups.

5. Students' final presentations

The groups of students approached the future-oriented activity in different ways. Before investigating in depth how the students' managed the activity, as will be illustrated in the Part studies, we provide a short description of the problems chosen, the simulations used to tackle these issues, the scenarios identified, and the main features of the desirable futures obtained. These descriptions are based on the final output of the groups, in the way they presented it to the other groups and the instructors during the final day of the course. In this sense, these descriptions are not supposed to reflect the complexity of reasonings carried out by the students during the long debates that came in the previous days.

Group 1

This group addresses the problem of the unfair distribution of wealth and resources in the world. To address it, they used the NetLogo simulation on cash flow to understand how the reserves of the banks influence the distribution of the money that exist in the system. In this simulation, the only parameters that can be changed are the number of people of the system and the reserves, i.e. the small portion of people's savings that the banks keep on-hand for transactions in cash form. Keeping the number of agents constant and changing the value of the reserves, the students obtain three scenarios which are evaluated on the basis of the resulting income distribution, i.e. how many poor, middle-class and rich people there are in the system. The first scenario is obtained with few reserves which lead to few middle-class people and many poor and rich ones; with an average value of reserves, the number of middle-class people increases, and the poor ones decreases with respect to the first scenario; increasing the reserves further, the middle class increases in number as well as the rich one while the poor gets very little. Once defined the third as the desirable scenario, the students identify that the main element that allows to obtain this distribution of money is the presence of a centralized and very powerful institute. While describing their choices to realize this scenario (e.g. making the UN as an executive body), the group also describes possible obstacles that could hinder it (e.g. autonomist movements of the local governments).

Group 1	
Problem	Unfair distribution of wealth and resources in the world
Simulation	Cash flow
Scenarios	1) Wide rich-poor gap 2) Increase of middle class 3) Increase of middle class and decrease of poor
Desirable future	Few poor people, many middle-class people
Actions	Creation and strengthening of a central bank institute

Group 2

This group addresses the problem of overpopulation. To study it, they use the wolf-sheep predation simulation re-interpreting its agents and parameters. For the first scenario, they only consider sheep as humans and grass as natural resources, putting the initial number of wolves at zero. In this way, increasing the grass regrowth time (as the time needed for the not renewable resources to become available again) and the reproduction rate of sheep (to reflect the acceleration of population growth), they notice that the population has grown in a way that the resources are inadequate to feed them all. In the second scenario, the wolves are introduced as the pathogens that threaten the population, and the grid is shrunk to simulate a further confinement of the humans. In this way it is observed that the wolves-pathogens reproduce fast, and the number of sheep-humans decreases. The desirable scenario is identified by "interpolation" of the two extreme scenarios showed. Indeed, the students envision their preferable future in the reach of a stable peak of the population. To obtain it, the group understands that the main factor to be achieved is the distributed wealth of people, and that it can be reached with international agreements and with a sustainable exploitation of the resources we have available. The main elements of this sustainable evolution are the innovations in energy sources, water supply, land use, urban planning, and hygiene norms. Once clarified the characteristics of the desirable scenario and the actions to be carried out, the students come back to the simulation and act on the parameters to reflect the features of the desirable scenario (e.g. the diminishing of the grass regrowth time reflects the sustainable development; the diminishing of sheep reproduction rate corresponds to the widespread wealth distribution; the de-powering of the wolves' parameters reflects an improvement in hygiene conditions). In this way, they can obtain a rapid growth of human population that is comparable with data we have today and then the reach of a stable peak, as wanted.

Group 2	
Problem	Overpopulation
Simulation	Wolf sheep predation
Scenarios	1) Depletion of resources and death of population 2) Spread of diseases and death of population
Desirable future	Stable peak of population
Actions	International agreements and norms for sustainable development (energy, water, land, urban planning, hygiene)

<u>Group 3</u>

This group addresses the problem of on-going globalization as a process of cultural flattening where the different traditions are cancelled. For this problem, the students imagine three different scenarios: a complete globalization where there is a worldwide cultural flattening; a globalization where isolated minorities survive; a scenario of equilibrium where different cultures live side by side without conflicts nor cultural predominance. After explaining the three scenarios, a student presented a simulation he had produced extending the voting model in order to explain the on-going globalization using an agent-based simulation. In this simulation, he included 14 possible opinions (instead of two) and added a dynamic of influence from random agents to simulate the presence of internet, without being limited to the change of opinion only due to physical closeness. Without internet, little neighborhoods of the same culture are produced (as in the classic voting model) while switching it on we observe a cultural flattening. The third scenario mentioned above is considered by the students as the desirable one, with an equilibrium among cultures. To realize it, the group outlines the revolutionary road toward 2040 including obstacles, conflicts, and bifurcation points that can lead to a scenario or another.

Group 3	
Problem	Globalization and cultural flattening
Simulation	Voting (extended)
Scenarios	1) Complete globalization and cultural flattening 2) Partial globalization with survival of cultural islands 3) Equilibrium among cultures without conflicts nor cultural predominance
Desirable future	Equilibrium
Actions	Revolution, internet

Group 4

This group addresses two problems related to the school system: the predominance of antiquate teaching methods and the stress experienced by students. To deal with these problems, the students identify preliminary solutions: on one side, the introduction of new technologies to facilitate learning and make it more interactive, on the other a change on the evaluation system (from numbers to letters). The simulation that the students used to study this issue is that on cooperation. They re-interpreted the agents and parameters of the simulation to describe the competition between supporters of traditional methods (greedy cows) and the supporters of innovative methods (cooperative cows); they both can survive thanks to the students' support (grass) but the innovative teachers want to collaborate with the students, while the others only want to dictate their ideas to them. The simulation displays three scenarios. The first, and desirable one, consists in reaching an equilibrium between old and new teaching methods; the second and the third show respectively an excessive use of technology or an exclusive presence of traditional methods. To reach the desirable scenario, which is described in detail, many actions are identified (e.g. mass movements, school politics that favor methods like the peer instruction, individual actions).

Group 4	
Problem	Predominance of antiquate teaching methods and stress experienced by students
Simulation	Cooperation
Scenarios	1) Equilibrium between traditional and innovative methods 2) Predominance of innovative methods 3) Predominance of traditional methods
Desirable future	Equilibrium
Actions	Mass movements, peer instruction, individual will

Group 5

This group addresses the problem of air pollution in the Po Valley (Italy). To do that, they use the NetLogo simulation named "urban suite - pollution" in which is modelled an ecosystem of people, trees, and pollutants. Varying the parameters of polluting and planting rates and the number of power plants, three scenarios are obtained. The first, obtained with realistic data, shows a constant increase of pollution and a stop after 20 years. The second, with a lower planting rate, shows a constant increase of pollution without any stop. The third scenario, that the students prefer, shows the reach of a plateau and a slight decrease of the pollution, and is obtained keeping the planting rate low and decreasing the number of power plants. Starting from these scenarios, the students identify possible solutions to the problem. In particular, their desirable future is a highly technological scenario characterized by politics for sustainability. To reach it, some actions are the unification of factories (the polluting factors) and the institution of programs of incentives for sustainable development.

Group 5	
Problem	Pollution in the Po Valley
Simulation	Urban Suite – Pollution
Scenarios	1) Increase of pollution and stop after 20 years 2) Constant increase of pollution 3) Reach of a plateau and slight decrease of pollution
Desirable future	Plateau
Actions	Use of technologies, unification of factories, incentives for sustainable developments

Group 6

This group addresses the problem of racial discriminations. Three scenarios are identified: in the first there is a return to the nationalisms of the past; the second consists in the prosecution of the present situation; the third is considered a utopian scenario in which race is not an important factor in society and there are more dialogue, tolerance, and freedom. The group analyzed two simulations (ethnocentrism and segregation) that related to the problem but did not use them to elaborate scenarios because of the pre-set levels of discrimination. To approach the desirable future, some actions have been identified, such as the concession of citizenship to those who pay taxes, educational actions, promotion of free exchanges and movements and the strengthening of institutions like UN.

Group 6	
Problem	Racial discrimination
Simulation	Ethnocentrism; segregation
Scenarios	1) Return to nationalisms 2) Business as usual 3) Elimination of races from the public discourse
Desirable future	Elimination of races from the public discourse
Actions	Improvements in education and institutional actions

Group 7

This group addresses the problem of the high levels of stress that the students experience today because of the school system. To address it, they re-interpreted the simulation of wolf-sheep predation by assigning a different role to the agents and the various parameters. More specifically, the stress is “personified” and is embodied by the wolves in the simulation; the students are compared to the students; the grass in the simulation is the free time that the students can find for themselves, despite the school workload. Changing the initial conditions of the simulations and the values of the parameters, the group identifies three behaviors of the simulated system that are at the basis of the future scenarios. The first scenario shows the elimination of the students/sheep that are eaten by the stress/wolves; the second leads to an uncontrolled proliferation of the students that nevertheless become weaker and weaker in absence of stress; in the third scenario there is an equilibrium between stress and students. Once defined the third as the desirable scenario, the students identify the necessary changes, and the things that are not needed to change, in order to reach that scenario. Among the various points of their action plan, they highlight the pandemic as an element of historical change that has raised politics' awareness on the schools and that has triggered a process of reformation. In particular, the group emphasizes the role of individual actions of the students (with public demonstrations, lobbying and personal hard work) to innovate the system.

Group 7	
Problem	High levels of stress experienced today by the students because of the school system
Simulation	Wolf sheep predation
Scenarios	1) Stress wins 2) Students win 3) Equilibrium
Desirable future	Equilibrium between stress and students
Actions	Public demonstrations, lobbying and personal hard work

6. Data analysis

In the future-oriented activity of this implementation, 5 groups out of 7 (groups 2, 3, 4, 5 and 7) imagined their preferred scenarios as strongly characterized by an idea of equilibrium. This equilibrium was interpreted in a different way for the various groups.

Group 2 worked on the problem of overpopulation and, after having explored scenarios in which the population ran out of resources or was threatened by infectious diseases, imagined a scenario by interpolating the two extremes previously identified. Observing the graphics provided by the simulation, they noticed that a situation of equilibrium between resources and humans was achieved when the curve reached a plateau (they call it a "stable peak").

Group 3 addressed the issue of globalization and imagined a future with a diversity of cultures that live peacefully, side by side, avoiding that only one culture takes the lead on everyone. Even if the idea of a peaceful co-living of cultures, without any conflicts not cultural predominance could suggest the idea of a "fake equilibrium" as the "equilibrium of perfection", the context in which this scenario was formulated contradicts this interpretation. Indeed, when the students outlined the story that led to that future, they considered many conflicting interests and a diversity of stakeholders which continue to co-exist in the final un-globalized scenario.

The problems chosen by Group 4 were related to the school system: the predominance of antiquate teaching methods and the stress experienced by students. They imagined three main stakeholders for their futures: supporters of traditional educational methods, supporters of innovative methods, and students. After having outlined two extreme scenarios (only educational methods or only traditional ones are used in the schools), they think to a future in which it is reached an equilibrium between old and new teaching methods where each of them works as a counterweight for the other and only their mutual presence can guarantee the realization of the students' objectives.

Group 5 worked on the problem of air pollution in the Po Valley (Italy). They explored different scenarios, including the business-as-usual and the worst-case scenarios, evaluating them based on the graph of pollution in time. Having understood that it is very difficult to make pollution lower, they changed the parameters until they reached a plateau behavior of the curve which they considered their desirable future. In this case, the idea of equilibrium consists in the fact that the plateau is reached through the balance of two factors, i.e. the number of polluting agents like factories and the trees planted.

Group 7 addressed the problem of the high levels of stress that the students experience today because of the school system. Also in this case, they formulated their desirable scenario as a scenario "between" two extremes: the elimination of the students that are psychologically defeated by the stress and the absence of any obstacle for students. The desirable equilibrium between stress and students is recognized by the group in the periodic evolution of the graph displayed by the simulation.

On the opposite, the two groups that did not cite any equilibrium in their analysis ended up with naïve scenarios that did not seem plausible neither to the students. For example, Group 6 worked on the problem of ethnocentrism and imagined a future in which no relevance is given to race in the society and no discriminations exist at all. But after their description of this ideal scenario, a student talks about it as a "utopian scenario" and then says it is "unreachable". Hence, it seems that the construction of desirable scenarios based on equilibrium produced more realistic scenarios that the students believed more feasible than "too perfect" futures that resulted to seem utopian because clearly far from a sense of reality.

Students' awareness about the types of equilibrium embedded in their scenario emerged in the last discussion of the course, after the students presented their works.

Instructor: Can you tell us something about the concept of scenario? And on the scenarios that you all have identified, on the type of scenarios you have used. You've all used a very similar strategy to think about scenarios.

F15 (Group 3): Probably at least as far as my group is concerned, first of all we took our ideal scenario and that had to be there… How I wish it were... even utopian, even if it was not feasible. And then the opposite scenario probably comes automatically in the sense that I have my utopian scenario and then if everything goes wrong, everything completely wrong what could happen, right? And then an in-between scenario, that is… what I want is not achieved, but neither it is possible to reach the most absolute catastrophe. At least, we have reasoned that way.

M8 (Group 2): For group 2 on overpopulation… for scenario 1 and 2 we took extreme cases. Even in the simulations, to try to have an obvious result, we exaggerated parameters so as to obtain results that were certainly as we expected. Then instead for the third simulation which was the one that we preferred and was a little more balanced…

Instructor: This is the other word you have all used. An equilibrium that is not a thermodynamic equilibrium, but a particular equilibrium… Which equilibrium? It is a form of equilibrium that you have all identified… Which form of equilibrium? What does balance mean in these situations?

M13 (Group 3): Well, it is a balance of a system that is not a physical system but also often a social one and which, however, reaches its own equilibrium and stops varying...

Instructor: It stops varying in what sense? Is it all dead?

M13 (Group 3): No, I mean… Oh my God… (laughs) It depends on the case.

Instructor: At the extremes, yes, because we arrive at a balance where everything stops.

M13 (Group 3): No well it depends on the circumstances... (laughs) defining it dead is perhaps a bit exaggerated but basically, yes, you get to a situation that then persists.

Instructor: But what is it that allows the balance to persist? What's this? What persists?

F17 (Group 4): Actually, in my opinion, a balance will be reached that can be defined as dynamic, that is, hybrid. Now it makes me think of chemistry right away... but this balance, however, does not persist. Well as we saw in the Voting simulations… it is not fixed… more or less the parts are those, but it is a continuous change, a continuous movement.

Triggered by a question of the instructor ("Can you tell us something about the concept of scenario?"), four students reacted by explaining how in the groups they constructed their scenarios. F15 is the first to take the floor and says the desirable future identified by her group (Group 3) was "an in-between scenario". Indeed, they started from two extremes, the utopian ideal scenario and its opposite, the worst-case scenario. Between these two extremes, they found the desirable future where "what I want is not achieved, but neither it is possible to reach the most absolute catastrophe". A similar strategy, that starts from the extreme cases, is followed by Group 2, as M8 tells. He emphasizes in particular the role of the simulation in defining these extremes: "to try to have an obvious result, we exaggerated parameters so as to obtain results that were certainly as we expected". Hence, extreme scenarios originate from extreme values of parameters, which lead to configurations of the system which are easy to interpret. When the extremes are clear, is identified an intermediate scenario which is "a little more balanced". This is the first time that in the discussion the word "balance" appears explicitly.

Then, citing the difference of this kind of balance with respect to the thermodynamic equilibrium, the instructor presses the students in order to focus better on the type of balance embedded in the scenarios ("Which form of equilibrium? What does balance mean in these situations?"). Here happens a little exchange of words between the instructor and two students from two different groups who two very different ideas of equilibrium.

The first student, M13, from Group 3, does not seem to have grasped the idea of thermodynamic equilibrium expressed by the instructor, indeed he says the equilibrium does not necessarily regard a physical system but a social one ("it is a balance of a system that is not a physical system but also often a social one"). Beyond this difference, he describes the equilibrium as something that is "reached" by the system and consists in the fact that the system itself "stops varying". Pressed by the instructor ("It stops varying in what sense? Is it all dead?"), M13 confirms that "it depends on the circumstances" but, anyhow, "you get to a situation that then persists". If his idea can be ascribed to a conception of *static equilibrium*, F17, from Group 4, cites the idea of a *dynamical equilibrium*. She refers to a system characterized by a balance of elements which remain more or less the same but recognizes that something always changes and does not freeze ("more or less the parts are those, but it is a continuous change, a continuous movement").

The notable thing of the interventions of M13 and F17 is that they both implicitly (M13) or explicitly (F17) refer to the voting model to exemplify their idea of static or dynamic equilibrium.
We can reasonably assume that Paolo is implicitly referring to the voting model as it is the simulation that he has extended up to 12 different cultures in his work on globalization. As we reported and described in the analysis of Chapter 7, he had obtained various evolutions of the system which, as a result of a process of self-organization, collapsed to an equilibrium status in which a static general flattening of the culture was observed. In fact, the reach of a static configuration is typical of the basic voting model too, as reported in the description of the voting simulation. That is why, it is reasonable that the equilibrium that he has in his mind is static and nothing changes.
On the opposite, F17 is probably referring to a different variant of the voting model in which, given a higher probability for the agent to change its vote, the evolution of the system usually does not converge to a static configuration. Moreover, we have to recall that in her group work she has widely discussed the simulations of prey-predator and cooperation where it is easy to obtain a situation of dynamic equilibrium between the populations of wolves and sheep or between cooperative and greedy cows.
In conclusion, from the analysis of the final discussion, some students were able to describe the process that led to the formulation of desirable scenarios and specifically of desirable scenarios of equilibrium, but the ways in which they conceptualize the type of equilibrium achieved strongly depend on the simulations taken as reference.

7. Discussion and conclusions

Analyzing the students' presentations, it emerged very clearly the importance that the groups gave to the idea of equilibrium in the construction of the different scenarios. This was surprising because, if for the futures studies the concept of equilibrium is at the basis of the formulation of scenarios (Kosow & Gaßner, 2008; Greeuw et al., 2000), this is difficult to be identified by novices reasoning on future-oriented issues. Indeed, in previous experiences within the ISEE project, the desirable scenarios imagined by students were always very extreme (Barelli, 2017). Indeed, the imagination of a desirable scenario triggered attitudes of detachment from reality that resulted in fictional, idealized futures that were static pictures of a future without any possible conflicts between interests or people. On the opposite, it is intrinsic to the notion of future scenario the description of a state of future equilibrium of the system. The equilibrium state, to be realistic, must foresee differences among interests and stakeholders, circular interactions between agents in the systems. In previous studies students' desirable scenarios gave back, instead, a picture of, metaphorically speaking, "thermodynamic equilibrium" where conflicts, interactions and differences among the stakeholders were minimized (Barelli, 2017). Even in the experience with university students (Barelli & Levrini, 2021), the type of scenarios obtained lacked this aspect of equilibrium and the students felt they were not reliable since they exaggerated specific aspects of a problem.
In the experience of the course with secondary-school students we have seen that an accurate work on simulations (carried out during lesson 3 and 4 with the analysis of three simulations of reference

and then with the establishment of correspondences with real-life issues) made it very natural for students to imagine scenarios of equilibrium, even if this concept had not been introduced explicitly.

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Part study 3 - Students' desires about the school of the future

1. Introduction

An unexpected result of the future-oriented activity was that many students used it as a way to look at school learning. Indeed, Group 4 and Group 7 selected issues related to school as the problems they wanted to address in the future-oriented activity. This part study is dedicated to the analysis of the ways in which the students talked about the problems of the school in the present and their idea of desirable school for the future. It is structured in three parts: in the first we present the reasons that led the students of the two groups to choose to address school related topics; in the second we analyze the main points of attention that the students considered in their presentations; in the third we collect and organize the main suggestions about school that the students expressed during the individual interviews.

2. Research Questions

This part study aims addressing the following research questions:

- RQ1. What are the reasons that led the students choosing a problem related to school for the future-oriented activity?
- RQ2. What are the features of the ideal school of the future imagined by the students?
- RQ3. What are for the students the main priorities for school's transformation? How did the module in general and the future-oriented activity in particular trigger these reflections?

3. Methodology

If the analysis in Chapter 7 about future-scaffolding skills was conducted essentially with a top-down methodology, this one is mainly bottom-up. It was structured in the following phases:

3.1. Bottom-up analysis of the groups' discussions

The first analytical phase had the goal of understanding the reasons that led the students to the choice of the problem. To do that, we focused on the initial parts of the video-recordings of the group work by Group 4 and Group 7, in which they discussed the problem to choose with a brainstorming activity. After having transcribed the video-recordings, we searched for the reasons that the students used to argue about the choice of a topic or another. In particular, we analyzed the differences that the students claimed between the topic of school and the others they mentioned during the brainstorming.

3.2. Thematic analysis of the groups' presentations

The second phase had the goal of analyzing the presentations of the same two groups in order to identify the main features of the students' ideal school in the future. We followed a methodology of thematic analysis (Braun & Clarke, 2006) where the bottom-up coding of the transcripts of the presentations was followed by a process of identification of themes in which the codes were organized in categories, namely the themes. The passage from the codes to the themes is a delicate methodological step since involves passing from something that is anchored to the specific set of raw data to more general categories that find confirmation also in the sociological or educational literature or in the findings from previous studies.

Operationally, the first step was building a grid as that reported in Figure 1, here exemplified with Group 7. We divided the transcripts of the final presentations and started coding with bottom-up tags (columns on the right).

Transcript	Bottom-up coding			
Noi abbiamo deciso di dividerci la presentazione tra di noi in modo tale che ognuno potesse presentare una parte del lavoro.				
E appunto abbiamo deciso di parlare della scuola nel futuro e in particolar modo del problema riguardante i livelli di stress a cui siamo sottoposti gli studenti nei percorsi di studi.	Problema	Stress		
Per trattare questa tematica abbiamo utilizzato come simulazione wolf sheep predation e all'interno di questa simulazione abbiamo identificato ciascun parametro ovvero lo stress gli studenti il tempo libero e li abbiamo identificati con una parte presente all'interno della simulazione e in questo caso abbiamo considerato i lupi come lo stress e le pecore come gli studenti e poi l'erba come il tempo libero che appunto gli studenti riescono a ritagliarsi nonostante i vari carichi di lavori. Dopodiché abbiamo analizzato tre diciamo scenari possibili				
Spero che si veda ancora perché ho dovuto aprire il microfono e allora io presenterò velocemente tre casi che abbiamo considerato per capire come potrà essere la scuola del futuro del 2040 usando questa simulazione. Per quanto riguarda il primo caso ci siamo messi questa ipotesi ovvero che lo stress sia talmente alto da fare in modo che quasi tutti gli studenti abbandonino gli studi. E ovviamente già dalla simulazione possiamo capire che la popolazione degli studenti inizierà a calare, calare, calare invece lo stress alla fine rimarrà a dominare su nessuno perché se non ci sono studenti ovviamente lo stress non può agire su nessuno. Invece il secondo caso è quello dove non c'è alcuna difficoltà, alcuna fonte di stress e quindi gli studenti cosa fanno? Diventano sempre di più. Tuttavia basta una piccola cosa una piccola difficoltà che crollano. Infatti basta un lupo in un gregge di pecore come per esempio questa immagine, e ovviamente il lupo... Possiamo già capire le conseguenze che potrà creare. Invece nel terzo caso e abbiamo deciso di vedere per esempio come integrare gli studenti e il tempo libero con anche lo stress. Infatti, si può vedere qui che la popolazione di studenti o comunque anche il tempo libero e lo stress seguono un andamento quasi periodico e stanno in equilibrio. Quindi gli studenti a volte magari possono avere delle fonti di stress quindi magari i progetti da fare lavori da eseguire. Però tuttavia continuano ad avere anche molto tempo libero a disposizione e quindi sono anche formati per poter continuare ad andare bene nel lavoro che trovano e che fanno				
E quindi andando avanti vedremo come abbiamo immaginato il 2040, la scuola del 2040. Per mantenere questo equilibrio nel 2040 tra lupi e pecore abbiamo pensato diversi cambiamenti e a diverse cose che devono rimanere invariate all'interno di questo sistema.	Cambiamenti e non cambiamenti			
Una fonte di stress, come sappiamo, per tutti gli studenti è il risultato finale di quel percorso ovvero quello dell'esame e attualmente sappiamo come le prove dell'esame influenzano molto nella valutazione finale e quindi abbiamo pensato di favorire maggiormente il percorso che viene svolto in tutti gli anni scolastici rispetto a solamente l'esame finale.	Causa di stress	Maturità	Valorizzazione percorso di studi	
Inoltre, anche nei compiti in classe i compiti in classe suscitavano molto stress all'interno cioè per gli studenti e quindi è necessaria una maggiore organizzazione non solo per quanto riguarda gli studenti stessi nel prepararsi in questi compiti ma anche tra gli insegnanti che dovrebbero cercare di distribuire in maniera migliore il carico di lavoro.	Causa di stress	Compiti in classe	Organizzazione studenti e insegnanti	
Abbiamo pensato anche che per migliorare lo studio degli studenti è necessario investire sulla tecnologia. Già in questo periodo la tecnologia sta prendendo piede all'interno di tutte le scuole ma pensiamo che si può migliorare ancora su questo aspetto.	Investimenti in tecnologia	Risorsa	Pandemia	
Ed infine un'altra fonte di stress è appunto quello che può essere il bullismo e quindi fare più attenzione appunto a situazioni in cui ci possono essere ragazzi soggetti a questo tipo di	Prevenzione del bullismo			
Però pensiamo anche per mantenere questo equilibrio è necessario mantenere alcuni parametri invariati, come per esempio i giudizi e i voti che servono per dare anche sprono agli studenti nel restare diligenti e continuare a lavorare costantemente.	Voti come sprono	Risorsa		
Un utilizzo parziale dei libri cartacei perché? Questo va un po' in contrapposizione con quello che abbiamo detto prima però pensiamo che, comunque sia, mantenere una parte dello studio sui libri sia necessario perché i libri possono dare alcune possibilità in più allo studente di organizzare lo studio.	Mantenimento libri cartacei	RIsorsa		
E infine anche le attività PTCO che pensiamo siano molto importante perché danno allo studente possibilità di applicare le proprie conoscenze fuori dall'ambito solo scolastico.	PCTO per applicare conoscenze	Risorsa		
Quindi adesso vedremo le azioni politiche e non solo che portano a questo cambiamento nel	Agency			
Allora dopo la pandemia le persone si sono accorte di quanto sia stata gestita male la scuola a causa delle indicazioni incerte che arrivavano sempre in ritardo	Pandemia	Presa di coscienza sulla situazione della		
e successivamente grazie alle manifestazioni e alle sollecitazioni degli studenti le loro idee sono state prese in considerazione dagli adulti.	Manifestazione	Agency studenti	Pandemia	
Queste manifestazioni hanno reso possibile un maggiore dialogo tra istituzioni scolastiche e studenti. Anche l'attenzione da parte del governo verso la scuola è aumentata infatti sono stati fatti degli investimenti finanziari. Infine, grazie a questi investimenti c'è stata un'innovazione del sistema scolastico, delle scuole e delle attrezzature. Sono cambiate tutte le cose che abbiamo detto prima.	Dialogo istituzioni-studenti	Innovazione	Pandemia	
In conclusione, dovremmo vedere quello che possiamo fare noi per migliorare la situazione.	Agency			
Abbiamo individuato due principali azioni che noi possiamo fare per migliorare la situazione per manifestare sia in senso stretto proprio le manifestazioni organizzate di cui si parla molto ultimamente e anche una manifestazione in senso più lato nel senso manifestare personalmente o anche a livello di classe i propri pensieri alla scuola.	Agency	Dimensione pubblica	Manifestazione	Dialogo studenti-prof-scuola
Quindi incoraggiare un dialogo tra gli studenti e professori e l'organizzazione scolastica.	relationship			
E la cosa finale e che forse non la più importante è la gestione da parte degli studenti nella loro autonomia dei compiti e dei progetti che devono svolgere perché si può manifestare finché si vuole, si può avere un sistema scolastico perfetto però comunque bisogna adoperarsi e bisogna fare il lavoro per ottenere dei risultati.	Agency	Dimensione di routine personale	Fare il proprio lavoro	

Figure 1. Exemplification of the bottom-up coding on the transcript of Group 7's presentation.

In this bottom-up process, the words or expressions used as codes are strictly connected to students' words. For example, a sentence like:

> *A source of stress, as we know, for all students is the final result of that path, that is the final exam and we currently know how the exam tests greatly influence the final evaluation and therefore we decided to favor more the path that is carried out in all school years compared to evaluating only the final exam. (Group 7)*

was coded with "cause of stress", "final exam" (in Italian: "maturità") and "enhancement of the whole study path".

After the bottom-up coding for both groups' presentations, the codes written were compared and grouped in 10 themes, as reported in Figure 2. It can be noticed that for the first two themes, two colors have been used. Indeed, the students talked about technological innovations and marks-provoked anxiety in two different ways. About technology, they wish for the use of more technological devices (darker yellow) but at the same time recognize the need to keep something on paper (lighter yellow). The same concerns anxiety: on one side they feel an enormous stress caused by marks and evaluation processes (darker green) but on the other they recognize the importance of forms of evaluation to keep students motivated.

Bottom-up codes - Group 4			
Problem	Teaching method		
Problem	Marks		
Technology	Solution to boredom		
Technology	Needs raised by the pandemic	Flank the paper books	
Source of difficulties	Marks	Passage from numbers to letters	
Technology	Pandemic as the trigger for change	Risks and benefits	
Technology	Help to students from the teachers		
Management of time	Teaching method	Same amount of information but more diluted	
Management of time	School in the afternoon	Tutoring with professors	Less autonomous study
Orientation	Career	Discover attitudes	
Physical activity			
Dialogue students-teachers	Relationship	Humanization of the teacher	
Trips	Internships	Knowledge more various	
Funding			
Routine	Rest		
Applied knowledge			
Routine	Time at school	Sport	Laboratories
School as care for relationships			
Time for themselves	Routine		
Government	Top-down intervention		
Agency students and teachers	Petitions	Movements on social network	
Experimenting change			
Teachers as protagonists of change			
Peer instruction			
Students agency			

Bottom-up codes - Group 7			
Problem	Stress		
Changes and not changes			
Cause of stress	Final exam	Enahnacement of the study path	
Cause of stress	Tests	Organization between students and teachers	
Technological investments	Resource		
Prevention of bullying			
Marks as push	Resource		
Keeping paper books	Resource		
PCTO to apply knowledge	Resource		
Pandemic	Reach awareness on the situation of school		
Protests	Students agency	Pandemic	
Dialogue institutions-students	Innovation	Pandemic	
Agency	Public dimension	Protests	Dialogue students-professors
Agency	Personal routine dimension	Do one's own work	

Themes

- Innovation passes through technology BUT traditional aspects are kept
- Evaluation as a source of stress: no abolition BUT softening
- Pandemic as an element of change/trigger of transformation
- School as a place of relationships
- Application of knowledge for the future career
- School determines routine and time management
- Agency (of students and teachers) in a public dimension
- Agency in a private dimension
- School as an institution
- Trade knowledge

Figure 2. Grouping of the bottom-up codes in themes.

To avoid redundancies, the themes were grouped once again as reported in Figure 3 to reach the seven macro-themes that we will illustrate in the analysis section.

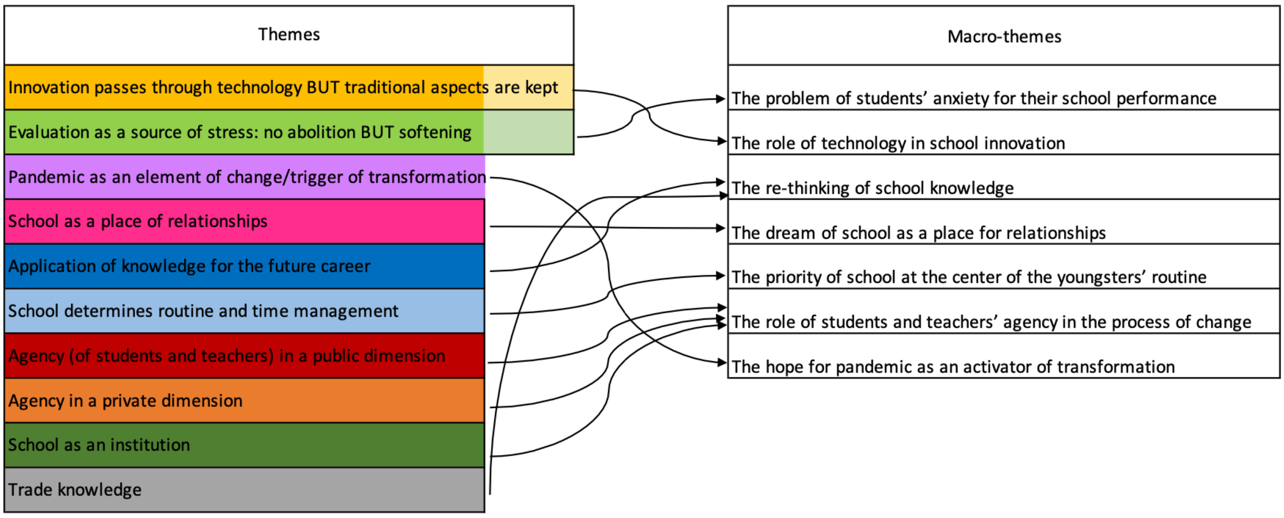

Figure 3. Grouping of the themes in macro-themes.

Once the macro-themes were identified, we looked again at the transcripts and improved the division in paragraphs according to two criteria. First of all, different phases of the activity (introduction, statement of the problem, introduction of the simulation, explications of the scenarios obtained with the simulation, presentation of the ideal future, and back-casting) could not be mixed in the same cell. Secondly, in each excerpt, only one macro-theme should have appeared.

At this point, we counted the number of words in each text excerpt to have a measure of its length and adjusted the height of the row accordingly. In this way, we were able to obtain a visualization for how the two groups' presentations were articulated in macro-themes and what was the relative frequency of each macro-theme with respect to the total coded part of the transcripts. We will provide more methodological details in the next section.

3.3. Bottom-up analysis of the students' interviews

To conclude the part study, we analyzed students' final interviews and in particular the parts of the interview in which they talked about their personal idea of school, the problems of school learning as it is nowadays, and how the future-oriented activity helped them in focusing their thoughts and the problematic issues. Differently than the previous parts of this study, here we do not consider only the groups that explicitly addressed school-related issues in the future-oriented activity, since all eight interviews have been analyzed (only 3 students belonged to Group 4, but the remaining 5 students did not address school in their final presentations).

The methodology followed here is basically a bottom-up coding procedure where we selected the excerpts of the interviews in which the students mentioned aspects related to school and then tried to highlight common issues that the students raised. This led to the identification of four macro-themes that we comment in the next section as a list of priorities that urge to be tackled to transform and improve school. The macro-themes identified in this phase partially overlap with those obtained at the end of the previous methodological step, but in this case the students reached a finer-grained level on the type of innovation in school teaching and learning that they wish for. In presenting the results, we will discuss the role of the module and of the future-oriented activity to trigger these reflections.

4. Data analysis and results

4.1. The reasons behind students' choices of school related issues for the future-oriented activity

After an initial brainstorming phase, both groups decided to address something connected to school. In Group 4, two main options had been identified: the problem of global warming and problems related to the school system. The reasons that led to the choice of the school instead of that of climate can be summarized in three points that we illustrate with the words used by the students during the group activity. The first thing is a matter of thinking at *practical aspects and practical choices* that can be undertaken to solve the problems. This is what, for M18, makes reasoning on the school easier than addressing a problem like climate change:

> *The school could be interesting because <u>we can think about what choices could be made</u> to solve the problem. With climate change, on the other hand, <u>it becomes much more complex to actually go and find practical aspects</u>. (M18)*

Strictly connected with the issue above, the second reason that the students used to argue the choice of addressing school-related issue was that this is *a problem closer to students' lives* and in which they feel to be directly involved.

> *It also has to do with how the job market could be... now they tell us to learn English well because it could happen that we have to go abroad because maybe we can't find a job... <u>this is a future that belongs to us particularly</u>... we could think about how to organize the school, the state to enhance the workplace in the future... and this actually encompasses various topics. (F17)*

> *If we think of <u>a problem closer to us</u> we can think of more perspectives... depending on what we have experienced... it can be a way to do a more in-depth work. (M16)*

As already mentioned by F17, the last reason of choice for group 4 was related to the fact that reasoning about school involves *thinking at a range of different aspects that cover many dimensions*, from the issue of job market to social and climate justice.

> *The particular thing is that if we try to treat the school in the future and how to advance it together with economic development, <u>there are many other issues within it</u>. The area of work, new professions... the area of social differences, racism... but also of climate change, for example... <u>you can find links in many areas</u>. (F17)*

For Group 7 the choice of the problem was between school and nuclear wars. The discussion was similar to that in Group 4, even if more concise. The main reasons for the choice were that the school is a problem in which the students are the protagonists and for which more practical actions can be imagined. On the opposite, they believe that the problem of nuclear wars can be solved only with top-down directives.

> *Let's choose school in 20 years because there is more space to imagine, while nuclear wars are a bit of a stupid problem. What are you going to do with it? You say "don't do it" and that's it. (M32)*

We see that, for both groups, problems related to school are perceived as closer to their life, in contrast to other huge global issues like climate change and wars for which the students feel not to be empowered enough to do anything with their concrete actions.

4.2. The problems of the school of today and the features of the ideal school of the future

To understand and describe how students imagined the future of the school, we analyzed the final presentations given by the two groups. We followed a methodology of thematic analysis (Braun & Clarke, 2006) where the bottom-up coding of the transcripts of the presentations was followed by a process of identification of themes in which the codes were organized in categories, namely the themes. The passage from the codes to the themes is a delicate methodological step since involves passing from something that is attached to the specific set of raw data to more general categories that find confirmation also in the sociological or educational literature or in the findings from previous studies. We will present the results of the analysis developing a narrative that goes across the themes identified, in order to give back a picture of the main problems that the students see in the school nowadays, the features of their ideal school and the type of transformative actions that need to take place.

The macro-themes that we identified are seven:

1. The problem of students' anxiety for their school performance
2. The role of technology in school innovation
3. The re-thinking of school knowledge
4. The dream of school as a place for relationships
5. The priority of school at the center of the youngsters' routine
6. The role of students and teachers' agency in the process of change
7. The hope for pandemic as an activator of transformation

Before presenting how the macro-themes are distributed in the two groups' presentations, we describe in detail each of the categories using students' words. After doing that, for each macro-theme we provide a short discussion of the findings against the research literature.

4.2.1. The problem of students' anxiety for their school performance

The traditional methods of knowledge assessment and evaluation are perceived by both groups a considerable source of stress for the students. In particular, the final exam of high school (in Italy, the "maturità"), is a sort of threat for the students during the whole school path.

> *And in fact we decided to talk about the school in the future and in particular <u>the problem concerning the stress levels to which students are subjected in their studies</u>. […] <u>A source of stress, as we know, for all students is the final result of that path</u> or that of the exam and we currently know how the exam tests greatly influence the final evaluation. […] In addition, even in <u>the classroom tests… the classwork caused a lot of stress</u> inside… that is for the students. (Group 7)*

> *Another point on which we have focused is the question of <u>school grades which we have noticed that let's say they put a little difficulty in the guys</u>. (Group 4)*

However, in a perspective of maintaining a certain balance within the system (as discussed in Part Study 2), they do not propose an abolition of texts, exams, and grades. Indeed, at a certain extent, forms of evaluation are believed to a fruitful resource for the students and helpful for learning:

> *But we also think to maintain this balance it is necessary to keep some parameters unchanged, such as the marks and grades that are also <u>used to encourage students to remain diligent and continue to work constantly</u>. (Group 7)*

To keep the motivation but reduce the stress connected to the marks, group 4 suggests, for the tests, to move from an evaluation in a 0-10 rank to a ranking with letters from A to F:

> *So we are not talking about a total abolition but a passage from grades expressed in numbers to votes expressed in letters of the alphabet, as is the case in America, for example. (Group 4)*

They do not explain the advantages of using the letters as a ranking system, but we can suppose that there is in the students a certain pop-cultural fascination for what happens in the USA, as an example of innovation. More ideas are proposed by the students of group 7 who reflects on the possibility of a better organization of the workload in order to avoid too many tests in a too short period of time:

> *And therefore greater organization is needed not only with regard to the students themselves in preparing for these tests but also among the teachers who should try to better distribute the workload. (Group 7)*

The teachers appear as protagonists of the change of school since the very first sentences of the presentation. Later on, they will illustrate how their role is essential for the transformation they hope for. To reduce the anxiety for the final examination, they ask for an evaluation system that takes more into account the achievements throughout the whole school path, without basing only on the performance in the exam.

And therefore we decided to value more the path that is carried out in all school years and not only in the final exam. (Group 7).

<u>Conclusion of the section against the research literature</u>

Even if some ideas proposed by the students can appear naïve (e.g. the preference of an American ranking system with grades in letters), the problem that both groups identify is of real concern for the young generations. The phenomenon of test anxiety has been widely studied from educators and psychologists since the 70s (Hill, 1972; Dusek, 1980; Wigfield & Eccles, 1989). However, the on-going pandemic and distance learning seem to have worsened an already existing problem (Christiansen, 2021; Korhan, Engin & Güloglu, 2021), with less motivated students but even more obsessed of performing at their best in every aspect of their life (Li, Zheng & Chiang, 2021). The phenomenon adheres to the recent construct of the "performance society" (Gancitano & Colamedici, 2018) that constantly requires that individuals share and demonstrate to others their optimal ways of living and succeeding. We think that it is significant that gifted students, as those enrolled in the course are, saw the anxiety against school as *the* problem that it is necessary to solve to arrive at the 2040 they hope for. And this is even more significant if we consider that they are in their penultimate year of high school, so the improvements and changes they reason about are not supposed to be operative during their own school itinerary.

4.2.2. The role of technology in school innovation

The technological dimension has a relevant role in the innovation of the school system that the students advocate. Its use is foreseen to contrast the traditional teaching methods that the students consider "boring and not very interacting".

We believe that <u>the classical notional and frontal teaching method is boring and not very interactive</u> and to make it… to improve it, let's say… we should make more use of digital devices in the classroom. (Group 4)

They say that technological devices are already part of some teaching activities, and the process has recently accelerated because of the massive implementation of distance learning imposed by the pandemic.

We also thought that to improve students' study it is necessary to invest in technology. <u>Already in this period</u> the technology is taking hold in all schools, but we think that there is still room for improvement on this aspect. (Group 7)

<u>It is a fairly current issue</u> because we have been at home for many months <u>with the Covid</u> issue. And the technology turned out to be quite useful… indeed a lot! (Group 4)

However, always in a logic of balance and gradual transformation, the students of both groups believe that the technological innovation must not replace traditional learning tools.

Technology is certainly a good teaching and learning tool, clearly if combined with paper and therefore with books. (Group 4)

Why partial use of paper books? This goes a bit in contrast with what we said earlier but we think that, in any case, keeping a part of the study on books is necessary because books can give the student some more possibilities to organize the study. (Group 7)

In particular, according to group 7, keeping textbooks made of paper is necessary in order to "organize the study". We can read, behind this apparently simple sentence, an as important as implicit belief of the students: if new methods (represented by the "technology") can innovate school making it more entertaining, more pleasant and less boring for students, it's from traditional methods (represented by the "paper" and the "books") that comes a precise and solid form of organization of knowledge and this organization is what allows the students to orient themselves in all the pieces of information. Coherently with this interpretation, we also have group 4 that imagines a use of technology that should also allow a closer interaction between teachers and students:

In particular we were also imagining a possible platform that allows a better synergy so that the teacher can also enter the work of each student to see in real time what he is doing, also allowing to better understand the reasons for which maybe he's stuck in a problem and then can't move forward. (Group 4)

This shows how technology itself needs to support the students in their learning processes but cannot replace the confront with the teachers as the repositories of organized, authentic, and validated knowledge. On the opposite, the platform that the students imagine are properly thought to facilitate the process of teachers' supervision on the students.
Group 4 also reflects on the health issues related to the widespread use of technological devices, imagining that those tools will be used only starting from middle schools.

In particular, we also considered how probably these new technologies will tend to become almost everyday life, perhaps even starting from middle school. Indeed, we have not considered the use of technological tools starting from the elementary schools precisely because spending many hours in front of screens from an early age can also lead to posture defects or even damage health and therefore there will most likely be strong opposition, which will also limit the use of technology with regard to the first years of school. And therefore will probably reach a level in which electronic devices such as computers and tablets will also be used with good frequency during lessons starting from middle school, in our opinion. (Group 4)

Conclusion of the section against the research literature

The literature in the field of Science and Technology Studies has been showing that both science and technology are central to young people's perceptions of the future (Angheloiu, Sheldrick & Tennant, 2020; Cook, 2016). In the FEDORA project we are widely investigating this aspect, considering the students' views of their personal future and the scenarios they imagine for their cities and for the society (FEDORA, 2021 - D3.1). Hence, looking at those data, it was not surprising that, thinking at the future of school, the students ended up reflecting about the role of technology in it. Since the 80s, the community of educators and psychologists has analyzed how technology would have challenged not only the teaching methods but also the same processes of learning. In a famous paper, Papert presents his critique to what he calls “technocentrism”, that it was envisioned for the school of the future (Papert, 1988). From the Piaget’s use of the term egocentrism, the word technocentrism is coined to reflect the idea that all educational questions can be referred to technological answers. The fallacy of technocentrism, for Papert, resides in the belief that the most important aspect of education is the fact that it is the provider of information or even the provider of access to information. From the presentations of both groups, it emerges a high consideration of the technology in schools, but it seems to respond, from one side, to a need of making the school learning more attractive and less boring, and, from the other, to the necessity to adhere to an already started process of transformation of society and also of schools. In this way, we do not recognize a “technocentric” perspective in the students’ imagination of the future. Indeed, behind their ideas we can read a deeply-rooted conception of school not as the Papert’s “provider of information” but as the organizer of information that hence makes knowledge accessible and learnable.

4.2.3. The re-thinking of school knowledge

In front of what group 4 calls “the classical notional and frontal teaching method”, the students do not only refer to technology as the solution for their problems. They imagine a variety of changes that need to be done in order to make learning, on one side, more pleasant for students and, on the other, more relevant for their personal future and careers.
One problem that the students experience is related to the frenetic rhythms of the classes, with a too intense concentration of information in a too short period of time:

> *Furthermore, we also imagined that new teaching methods adapt to a new management of times that for us needs to be improved a little. In fact, the lessons seem perhaps too dense and therefore very often it also becomes difficult to be able to better grasp all the notions that are provided to us. So we also imagined perhaps longer lessons that contain the same amount of information so that the latter are diluted over time. (Group 4)*

For group 4, knowledge requires time to be assimilated and understood, while the actual organization of the school timetable and the curricula implies dense lessons in which a lot of information is given. They not only think at a remodulation of the rhythms of the classes, but imagine also that the type of knowledge provided should be rethought:

> *Clearly the lessons in the morning are less notional lessons but lessons in which things are taught but there is also a lot of talk about the concrete, well, application. (Group 4)*

The “notional” lessons are counterposed with the “concrete” character of knowledge they would like to learn. They believe that school should teach more the applicative issues embedded in the disciplines in order to prepare the students for the world outside and after the school. They clarify this point later in the presentation, referring to other school activities to implement:

And then in the afternoon we thought that going back to school could actually be very useful. Immediately after, we also noticed how having the afternoons available to students seems even more incentivized to take courses that could also lead them to approach experiences that they have never done in their life and in doing so they could also have a better idea of which may be their attitude. It could also be useful for orienting them to a university course. […] Furthermore, we also imagined that in the future school trips or internships could become more and more present to acquire new knowledge much more varied than those that can be learned at school. (Group 4)

A similar perspective is expressed by group 7 too:

And finally also the PCTO activities that we think are very important because they give the student the possibility to apply their knowledge outside the school only. (Group 7)

The students imagine a variety of activities with which the school curriculum should be enriched: courses in the afternoon, school trips, internships, university, and career orientation activities (they cite, for example, the PCTO activities, "Percorsi per le Competenze Trasversali e l'Orientamento" that are programs in Italy aimed to develop transversal competences and prepare for the university or professional choices after high school). All these are experiences that already exist in the school and that are present in the official curricula. The emphasis that the students give on them is significant of their appreciation of engaging in activities that allow to widen the knowledge learnt in the classroom, to find application contexts for that knowledge and to understand their attitudes.
Another difference between the school they experience and that they would like is related to peer instruction:

Another important point is peer instruction, something that is already present now but is not being exploited enough. In fact, most of the students who join these projects do it for personal remuneration, therefore as school credits, and do not actually think about how effective these opportunities are. For this it would be useful to publicize these events and make them common in all schools. (Group 4)

The suggestion of introducing peer instruction in all schools can be interpreted as another dimension of change in the forms of how knowledge is constructed. According to students' ideas, the teachers will not be the only repositories of knowledge but there can be some spaces during the school routine in which some form of knowledge is actually developed thanks to the interaction with mates. This point will be furtherly discussed in the following paragraph, in which the role of relationships within the school environment will be pointed out.

<u>Conclusion of the section against the research literature</u>

From students' presentations three main problems were identified in how the knowledge is currently proposed at school: it is too condensed in time slots, lacks a focus on practical and application aspects, and does not pass through a relationship dimension.
For what concerns the rhythms of school, the students seem to experience in the current organization of school timetable an aspect of the on-going social acceleration which characterizes many aspects of our current lives (Rosa, 2010). In the school setting this is manifested with a conception of an instruction in function of the timetable, that results to be always "against the

clock": it demands, to students and teachers, to do more things, innovatively, on time, achieving better academic results and meeting higher standards. This conception is the opposite of the idea of the idea of school that is embedded in the Greek term "scholè" that has a range of meanings among which there are "free time" and "undestined and unfinished time" (Masschelein, 2011). This conception better responds to the students' need to have time for their own, engaging in experiences that surpass a chronological view of time, revealing the value of pause and the satisfaction of living a present time where there is no need for an outcome other than enjoying the present (Marini & Rodríguez Merchán, 2020).

4.2.4. The dream of school as a place for relationships

An element that characterizes students' ideal school is the quality of relationships between the protagonists that live the school in the first place, which are students and teachers. Group 4 extensively talks about this point in the presentation:

> *It could also be convenient to use the afternoon so that you can also organize hours in which students can meet to do group study, perhaps even with some professors. […] Furthermore, with the increase of afternoons spent at school, human relationships would be favored both between students and between professors and students, making sure that we also re-evaluate what is our image of the teacher who otherwise is seen as an austere character who wants to put us in difficulty only when in reality is still a person who perhaps shares our same interests… and a better bond could also be created.*

The ideal school dreamt by the students is centered around relationships. And there is more than that, if we put together the students' words presented in this paragraph with those in the previous one. We can read a sort of positive feedback that makes the school environment as a carrier and support of relationships between students and between professors and students, but the quality of these relationships makes school learning more effective, and the school environment results enriched. These relationships are exploited in different activities. In the previous paragraph we have already mentioned peer instruction, but there are other kinds of moments in which students can for example meet to study in groups or with a professor. In these activities in which the teacher participates in the moments of study, the students can "re-evaluate" the "image of the teacher", establishing a "bond" with them.

Conclusion of the section against the research literature

In the last 90 years, the educational community has been investigating the role of relationships at school to foster students' learning and well-being. From the students' words, two main kinds of relationships are identified: student-student and student-teacher. Between the 30s and late 70s, the educational psychology traditionally focused on the second type of interaction, assuming that, at school, not only the students' learning but also their socialization strictly depend on their relationships with teachers (Johnson, 1981). Since the 80s, new research perspectives have considered the importance of student-student interactions even within the school environment so that, nowadays, both teacher-student and student-student relationships are considered essential for the youngsters' development (Baker, Grant & Morlock, 2008; García-Moya, Moreno & Brooks, 2019; Bakadorova & Raufelder, 2018). In particular, recent studies have been focusing on the role of these relationship to trigger students' societal involvement and agency in social context (Wanders, van der Veen, Dijkstra & Maslowski, 2019). This will be discussed further in the sixt paragraph of this section.

4.2.5. The priority of school at the center of the youngsters' routine

In the second and third paragraph, we have already introduced some elements regarding the different organization of time imagined by Group 4. For example, they mentioned the idea of the fair amount of time needed to learn and appropriate disciplinary concepts, or the necessity of spending extra time at school in the afternoon to strengthen relationships with mates and teachers. They also mention that more time spent at school would reduce the time spent by students for their individual study:

> *It could also be convenient to use the afternoon so that we can also organize hours in which the students can also come together to study in groups, perhaps even with some professors. We have also noticed that in this way the time available could also grow exponentially because we will have time for a quality study that would allow us to reduce the time to devote to self-study. (Group 4)*

From these words, emerges the desire of the students to have back the time that in their routine they spend at home and devote to self-study. Later in the presentation, they sketch out a normal day in their ideal future:

> *Yes then I say we tried to imagine what a day could be for us students in our best future, in case all our projects have gone in the best way. So we thought that in the morning there could be lessons like now but from 9 am to 1 pm, so do 4 hours... so start a little later than now... okay let's not consider the situation of the virus that in our ideal future, in our ideal day the pandemic should already be over… so let's imagine a normal day without virus. So four hours of lessons for all students that end at 1 pm when begins with a lunch break that can be used to eat but also to rest. Because then in the afternoon from 2.30 pm to 5 pm... then it is clear that we have given a bit of an image but objectively then you can change it, you can think for a moment how to do it better... but during these hours it may be possible laboratory activities or meetings with experts with visits such as trips or visits for example to museums… and also for example the sports discourse because actually nowadays the life out of school is considered an obstacle for a student... Then from 5 pm, let's say, the personal activities can begin. So if one needs further study, he can study again or he can already begin to rest or carry out his fun and relaxation activities. This is an aspect that we think there is not very much today… time for oneself today is a bit neglected because in any case we are always busy with tests and checks during the whole school year. Maybe even the management of the school timetable as it is distributed throughout the year... maybe avoid leaving three summer months but dividing it better could be very functional. And then the evening is time to dedicate to friends or family which are increasingly important in life. This is a bit like our ideal day.*

For these students, the school results the main place around which the youngsters' routine should be centered, with 8 hours spent there every day. School seems to be so important that includes in it almost every aspect of the students' life: the access to institutionalized knowledge (with the most traditional classes in the morning), the experience of fields of application of what they have learnt (with the laboratory activities, meetings with experts or trips), the cultivation of meaningful relationships with teachers and mates (during the group study or lunchtime), the practice of recreational activities like sports. With the imagination of the future ideal routine, the students display the need of an almost fully institutionalized routine, where most dimensions of life are covered by the school program. However, it is actually thanks to this dense timetable that the school can contribute to free the time that the students have beyond school, like the "time for themselves" that the students claim to need and the relationships with friends and family.

<u>Conclusion of the section against the research literature</u>

Beyond some specific features of the ideal school of the future that reflect result of other studies (Kayikçi & Turan, 2020), the description of students' future routine points our attention on an issue that has been recently investigated in the educational research, i.e. the relationship of students with time and in particular with their own routine. In a study conducted in the early phases of COVID-19 pandemic, Levrini and colleagues (2020) pointed out three main conceptions of time: time as an opportunity to immerse yourself in experiences, time as agenda and time as an empty container to fill. In our case, the time of students is mostly experienced in one place, the school, and this place becomes the sources of almost all the social experiences in which the students are immersed. Far from being only an agenda (we could call it more a timetable) or an empty temporal box to be filled, the desire of time dedicated to school seems to adhere more to the first conception identified by Levrini and colleagues (2020). The experiences lived at school make time flourish, since it is enriched by knowledge, relationship, and entertainment.

An additional thing that can be noticed of students' imagined routine is the need that they have of rest: they imagine starting school later (at 9 pm, while in Italy the average time of school starting is 8 am) in order to sleep more, to rest after lunchtime and do not want homework after school because the time they want has to be dedicated to friends and family. This echoes many international findings in the research literature that show how the prevalent feeling of students toward school is tiredness (Moeller, Brackett, Ivcevic & White, 2020; Gariépy, Janssen, Sentenac & Elgar, 2016) and resonates with the sociological perspective that calls our society the "burnout society" (Han, 2020) also called the "society of tiredness", as a response to the request of continuous performance.

4.2.6. The role of students and teachers' agency in the process of change

One of the most frequent macro-themes identified in groups' presentations was the importance of students and teachers' agency in the process of realization of the desirable future. Their agency covers three main dimensions: the *public* (establishing a relationship with the institutions), the *professional* (involving the relationship with colleagues) and the *personal* dimension (carried out in the personal routine).

The public dimension is identified when the students talk about collective protests, marches, and petitions at which students and teachers take part or when they refer to awareness campaigns on social media or in the schools. All these forms of actions relate to the public dimension since they have the explicit goal to raise the government's attention about the situation of the school (petitions, marches, and protests) or to involve others in the movement (campaigns on media):

> *Then after the pandemic people realized how badly the school was managed due to the uncertain indications that always arrived late and subsequently thanks to the demonstrations and requests of the students their ideas were taken into consideration by adults. These events have made possible a greater dialogue between educational institutions and students. The attention from the government towards the school has also increased in fact financial investments have been made. […] We have identified two main actions that we can do to improve the situation. The first is to manifest, both in the strict sense precisely with organized events about we have been talking a lot lately, and also a manifestation in a broader sense, in the sense of manifesting one's thoughts personally or even at a class level, to the school, so encouraging a dialogue between students and teachers and the school organization. (Group 7)*

> *For this it is necessary a sort of activism on the part of students and teachers who can therefore make petitions or even movements on social media to the mass media. In this way, many more people would come into contact with this thought and maybe it would also spread the fastest way since we can exploit a tool that is still very prevalent today in the life especially of young people. […] Finally, an effort is needed on the part of everyone, especially the students. In fact, it is the students themselves who mobilize themselves to bring about a change in Italian education. For this it is necessary to awaken in a certain sense the students from the passivity that lies in these days, in this period. More than passivity I would say indifference towards the school, since now it is almost like torture many times. For this we need movements that can reach everyone, so that they realize that the school can change and they can do something to help. (Group 4)*

We can recognize that with the idea of agency in the public dimension comes the recognition of the roles of institutions with which, as said by group 7, a dialogue can be established. Moreover, the students realize that acting on a public dimension is not limited to the dialogue with the higher-level institutions (e.g. the government) but also involves mid-level actions of awareness-raising at the class or school levels.

If the public activism involves students and teachers who take part together in the transformation of the school, the second dimension of agency, the professional one, regards mainly the teachers. Especially group 4 focuses on the fact that, to trigger the desired transformation, the teachers need to take part in courses of professional development where they work together with their colleagues to figure out ways to innovate their teaching and, hence, school.

> *Furthermore, it is also difficult to find teachers willing to try new teaching methods. In this case, projects or courses could be set up for the teachers themselves so that they have the opportunity to discuss with each other to devise new teaching methods and perhaps even discuss them with the students in order to have their approval. (Group 4)*

The last dimension relates to the personal agency of students that covers the context in which they act without interacting with institutions and peers but in their personal lives and routines. Group 7, for example, focuses on the hard work of students in order to "get the work done" personally.

> *And the final thing and perhaps not the most important is the management by the students in their autonomy of the tasks and projects they have to carry out because it can manifest as long as you want, you can have a*

perfect school system but in any case you have to work and you have to get the work done to get results. (Group 7)

Conclusion of the section against the research literature

Even if there is no global consensus on the definition of "student agency", something that lies at the basis of the different conceptualizations is a general sense of responsibility that the students perceive of themselves as members of society who can influence other people, events and circumstances for the better (OECD, 2019). Since agency implies being part of a multi-actor context, the idea of individual agency is often flanked by the so-called "co-agency" or "collaborative agency" (Glăveanu, 2015). In our case, when students talk about the possible actions that they can do to create the school of the future, they include the teachers as their allies in the process of transformation. The alliance between students and teachers to improve school is a rather new finding in educational research. For example, Jones and Bubb (2020) report that many students indicated some uncertainty about the possibility of students and teachers being able to bring about improvement together, because of very distant ideas about how an ideal school should be ("Teachers learnt at a different time from us. The school system should change with the generations", "Adults see things in a different way from children").

In students' words we identified three dimensions of agency: the *public* (establishing a relationship with the institutions), the *professional* (involving the relationship with colleagues) and the *personal* dimension (carried out in the personal routine). These can be conceptually associated to the three "spheres of transformation" (O'Brien & Sygna, 2013; O'Brien, 2018) that are the practical, the political and the personal one. In this model, the practical sphere is usually associated to the idea of transformation throughout expertise and in our case is connected to the professional dimension of agency. Then, the political sphere can be linked to the public agency, since in both case an impact on institutions and societal structures is implied. Finally, we have the personal sphere which is the most blurred of the three. Indeed, following O'Brien, this is the sphere "where the transformation of individual and collective beliefs, values and worldviews occur" (O'Brien & Sygna, 2013, p.6). In our case, students' words to describe this change cannot be explicitly associated to values and worldviews, because they are more linked to an aspect of routine and to a very local agency made of concrete actions. In some sense, the personal dimension of agency can be interpreted as another shade of the practical sphere of transformation.

4.2.7. The hope for pandemic as an activator of transformation

Throughout the whole presentations, both groups referred to the role of the pandemic (that in their scenario of 2040 occurred twentyish years later) in the process of transformation of school. From one side, the pandemic raised the issue of the importance of technology, that we already addressed with the analysis of the first macro-theme:

It is a fairly current issue because we have been at home for many months with the Covid issue. And the technology turned out to be quite useful, indeed a lot. […] We have analyzed that in the course of this pandemic the use of technologies is becoming more and more recurrent. (Group 4)

Abbiamo pensato anche che per migliorare lo studio degli studenti è necessario investire sulla tecnologia. Già in questo periodo la tecnologia sta prendendo piede all'interno di tutte le scuole ma pensiamo che si può migliorare ancora su questo aspetto. (Group 7)

But the importance of pandemic was not only that of suggesting a way of change like the use of more digital devices but was also a trigger of transformation. Indeed, as group 7 points out:

Then after the pandemic people realized how badly the school was managed due to the uncertain indications that always arrived late and subsequently thanks to the demonstrations and requests of the students their ideas were taken into consideration by adults. These events have made possible a greater dialogue between educational institutions and students. The attention from the government towards the school has also increased in fact financial investments have been made. Finally, thanks to these investments there has been an innovation of the school system, schools and equipment. All the things we said before have changed. (Group 7)

Again, the importance of students' agency is underlined. Indeed, the group recognizes retrospectively the role of the protests occurred during the pandemic in starting a durable change. The students' actions actually made the difference because the government decided to make more financial investments to improve the school system. In some sense, for both groups, the pandemic created the conditions for the realization of the desirable future.

<u>Conclusion of the section against the research literature</u>
If the school culture is often retained static and resistant to changes (Delpit, 2019), in the early phases of the pandemic the school systems needed to adapt and react almost instantaneously (Loose & Ryan, 2020). Even if there are authors who believe that the re-organization of school due to the emergency situation will not lead to permanent changes or transformations (Sahlberg, 2020), others, especially with the first outbreaks, saw the pandemic as an opportunity to rethink educational systems and, specifically, science education (Reiss, 2020; Levrini et al., 2020). In their presentations, the students emphasized the role of pandemic as, on one side, something that exacerbated a transformation that was already in act (e.g. the use of technology for teaching and learning), but on the other side as an event that raised an unprecedent attention of the public on the school and its need of change.

After having presented the meaning of the different macro-themes, in Figures 4 and 5, we report, with two different visualizations, the distribution of the macro-themes in the two groups' presentations. In both figures, on the left there are the pie charts for the frequency in the transcripts of the seven macro-themes. The pie charts contain a first graphic with the percentage of the coded and uncoded transcript (coding coverage) and then it is reported the details of the percentage distribution of the seven categories on the coded portion of the transcript. All the numerical values have been calculated using the number of words in each excerpt. The second visualization, on the right of Figures 4 and 5, consists in the miniatures of the transcripts of two presentations (the readable versions are reported in Appendix H) with the distribution of the macro-themes. In this case, the height of rows is proportional to the number of words in the specific excerpt of transcript.

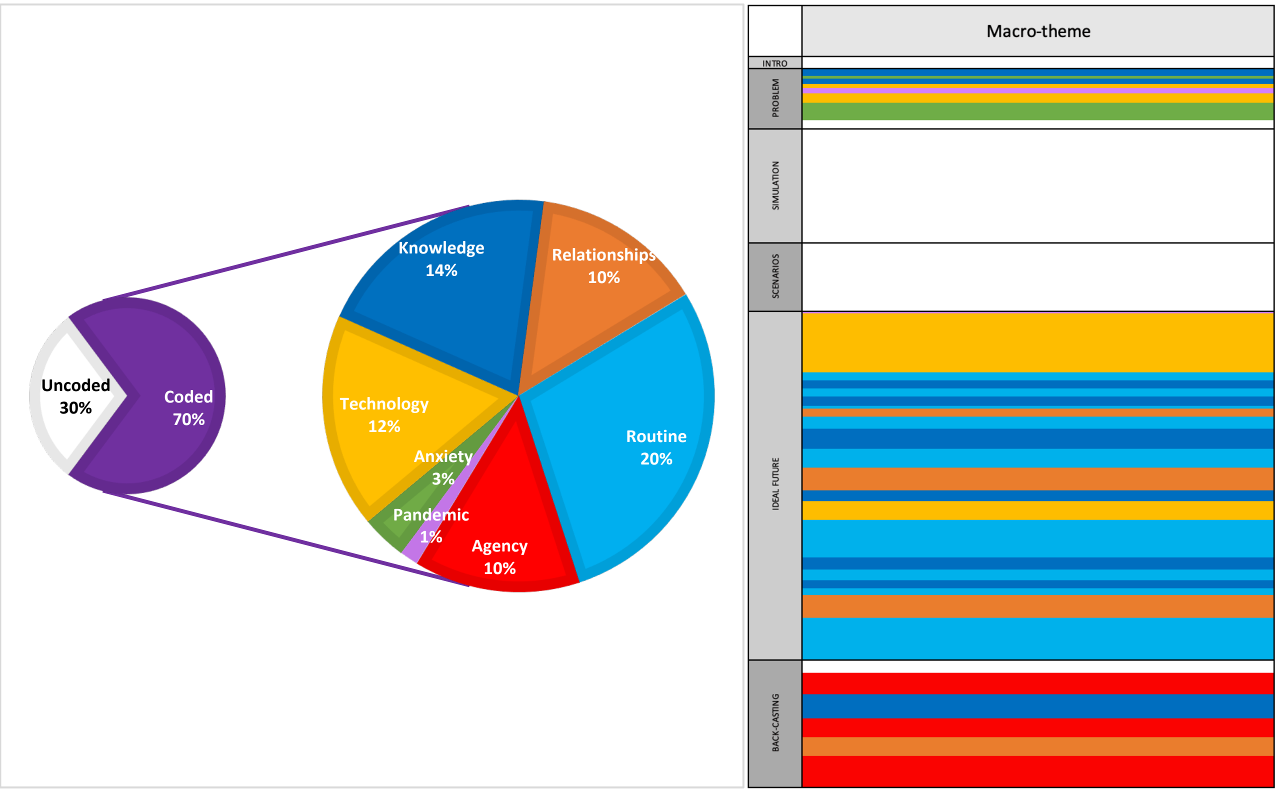

Figure 4. Distribution of the macro-themes in Group 4's presentation.

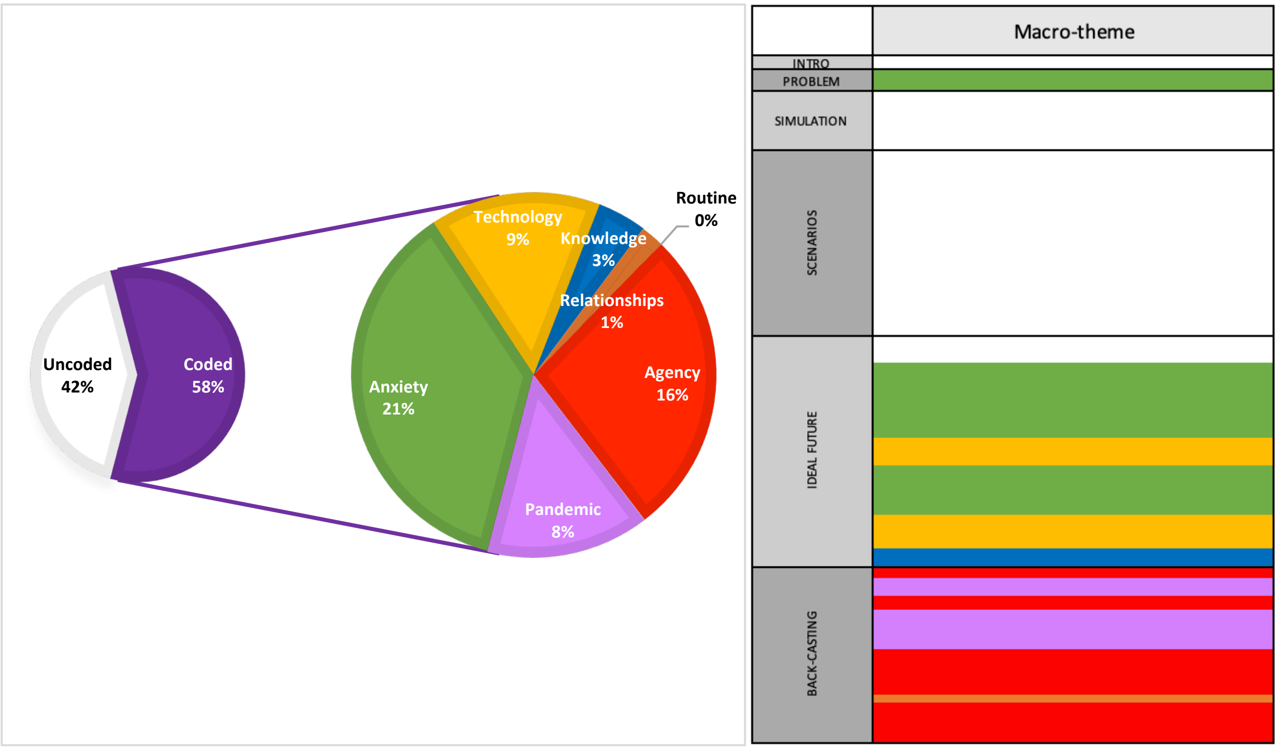

Figure 5. Distribution of the macro-themes in Group 7's presentation.

The difference between the two kinds of visualization is that in the second we have the chronological articulation of the occurrence of the macro-themes across the development of the

presentation. In particular, we have divided both presentations in six phases that were introduced and identified by the students themselves as a consequence of the articulation in tasks of the activity. These phases are: introduction, statement of the problem, introduction of the simulation, explications of the scenarios obtained with the simulation, presentation of the ideal future, and back-casting.
Even if the two presentations are very different for their extension (more than 2300 words for group 4 and less than 1000 for group 7), we can draw some common considerations about both.

Uncoded pieces of transcript – A first observation is methodological and can be done looking at the portions of coded and uncoded transcript. In both cases, we notice that there are significant parts of the transcript that could not be coded using the seven macro-themes. This percentage is of 30% in group 4 and grows up to 42% in group 7. Apparently, this would mean that from the bottom-up phase of coding to the identification of the macro-themes, many excerpts of text could not be captured by the macro-themes. However, if we look at the right part of Figures X and Y, we can notice in which parts of the presentation there are the uncoded parts. For both groups, most uncoded parts are in three phases: in the short introduction to the presentation, in the phase of description of the simulation and in that regarding the scenarios obtained using the simulation. This is all but unexpected for us. The reason behind the absence of coding in the introduction is rather trivial: here, the students briefly summarized the content of the presentation, the name of their group and outlined the general structure of the presentation, without entering the content of their investigation. We can easily explain the absence of macro-themes in the other two phases too: those parts of the presentation were interpreted by the students as the most technical ones, in which they had to "play the role" of scientists and experts of simulations, presenting the reasons for the choice of the model and showing its functioning. If we exclude these three sections by the count of the uncoded transcript, we notice that remain only few excerpts. Both for Group 4 and 7, they are positioned at the joints between the sections and are actually sentences that have to make the connections between one part of the discourse and the following. For example, the sentence that begins the section on the ideal scenario for group 7 is:

> *And then moving forward we will see how we imagined 2040, the school of 2040. To maintain this balance in 2040 between wolves and sheep we have thought about several changes and several things that must remain unchanged within this system. (Group 7)*

The same, for group 4, is the sentence that connects the section about the description of the problem to the part related to simulation:

> *This is a bit of the description of the post regarding the problem. Now I leave the floor to Francesca who will talk about the simulations we used. (Group 4)*

Throughout the comparison between the uncoded pieces of transcript and their position in the "economy" of the whole presentation, we can conclude that the number of excerpts that do not fall under the macro-themes identified is not an indicator of an inaccurate methodological step from bottom-up coding to the grouping in macro-themes.

Agency and back-casting – For both groups, we can notice that in the back-casting phase are concentrated the excerpts related to agency (in red, following the color coding). To explain this, we recall that in this part of the activity, and consequently in this part of the presentation, the students had to think about the possible events that could have led to the desirable future in 2040. Of the range of possible events and actions, the students emphasize the role of their own agency, as students, in changing the system.

Pandemic – We have already discussed how the students imagined the role had by pandemic on their possible and desirable futures and talked about this in the presentation. However, the two groups mentioned the pandemic in different parts of the presentation. Group 4 dedicate only a very small part of the presentation (around 1%) to this issue. In particular, they used the pandemic as the starting point to introduce the problem of their interest (the resistance of the school to innovate, also technologically, its methods) and then they mention it at the beginning of the description of their ideal future that is partially inspired to the use of technologies experienced in the on-going pandemic. For group 7, the reference to the pandemic is much more frequent (around 8% of the total presentation) and concentrated in the back-casting phase. This indicates that the students recognized in the pandemic a historical moment in which specific actions, such as public protests and petitions, have been possible: for them, the pandemic (and what happened during it, especially in terms of social awareness and agency) is part of the sequence of essential actions that can create the desirable future.

The predominance of routine – The biggest difference that can be noted comparing Figures 4 and 5 is the appearance, in the figure related to group 4, of the macro-theme of routine that is totally absent in that related to group 7. This macro-theme covers around 20% of the whole presentation of group 4. This can be partially explained with the same choice of the group 4 about how to structure the presentation. Indeed, the second half of the section about the explication of the ideal future was dedicated by the students to present their daily routine in the preferred 2040. This made explicitly recognizable the macro-category related to routine. However, the high frequency of the macro-category does not only depend on the choice of presentation because even in the first part of the section the category was highly present.

The role of anxiety – Another category whose frequency differs a lot between the two groups is that related to the issue of students' anxiety toward school performance. If in group 4 this macro-theme covers 3% of the presentation, this percentage grows up to 21% in group 7. Observing the position in the presentation of the macro-theme, we notice that for group 4 it is part of the introduction to the problem, alongside many other themes related to the role of pandemic, of school knowledge and of technologies. In the following sections of the presentation, the issue is not touched again because they mainly focus on addressing the issue of technological innovation as a response to the problem of teaching methods. On the opposite, for group 7 this macro-theme is more organically present in the presentation. The only problem they mention is the students' anxiety toward school and it is not surprising that, in describing their ideal future, this dimension occupies large parts of the section.

4.3. The priorities for school's transformation as inspired by the module

However, beyond the ideas had by the students, during the final interviews emerged students' finest thoughts about what is school for them, what are the problems of school learning as it is nowadays, and how the future-oriented activity helped them in focusing their thoughts and the problematic issues. We identified some macro-themes in the students' answers that we can summarize in the following list of priorities:

- Approaching school learning to contemporary challenges
- Connecting school disciplines
- Preparing for future careers
- Valuing teamworking as a knowledge building methodology

We explore each of these priorities citing and commenting students' words.

4.3.1. Approaching school learning to contemporary challenges

To trigger students reasoning on contemporary complex challenges was one of the goals of the course. From the interviews we can say that the students not only recognized that complex challenges exist but that they can be addressed through education and, specifically, through science education. However, the students said that this focus on current issues was new for them since they are used to traditional schooling methods that do not foresee this kind of emphasis on real world problems.

For example, Valeria says:

> *In my opinion it is precisely the mistake of the school not to do projects or to try to involve them [the students] in current problems and if anything to connect the subjects with each other in such a way that one can really realize what is the use of studying these subjects because in my opinion the fact… when one loses interest is because he does not see a purpose in what he is doing and if instead one, that is… takes the notions and then re-elaborates them, he understands that in reality everything he is studying is leading somewhere and it is not just placed there. (Valeria)*

For Vittoria, addressing "current problems" at school is a way for the students to "see a purpose" in what they are studying, as opposed to the idea of knowledge "just placed there", which is communicated by the teachers to the students, but it is not re-elaborated and cannot find any space of application. On the opposite, an approach that includes the attention to real-world problems can give a direction and a goal to learning ("he understands that in reality everything he is studying is leading somewhere"). She clarifies this concept in another excerpt:

In other words, in my opinion the school has this, it has this characteristic that, if anything, it informs you but then it does not help you to metabolize things, that is, it leaves them there in suspense and if one does not do a personal work... that is, they are notions that one has and just in case in the future it could withdraw out but momentarily they are there, they are stagnant in the sense they seem useless. (Valeria)

The new school oriented to real-world issues is for Vittoria a way to engage the students in the learning process. Indeed, they are required to have an active role in their education path and to do a step further than the assimilation of disciplinary notions: they have indeed to “metabolize” and “re-elaborate” the pieces of information provided to them and make knowledge flourish.
She also points out that it is very important the connection between subjects to address current complex issues, but this is something we will address in the next paragraph.
Another student, Davide, reflects on the difference of the problems addressed in the course with respect to traditional school issues:

Perhaps the element that enveloped the whole a little was the halo of generality, that is, the halo of "let’s consider everything", not just an element, because usually at least as a scholastic model, as a model, many assumptions are made, consider only small parts, I mean very sectoral problems. In this part I have seen much more generality. Perhaps speaking of topics very distant from yours, however, we saw that there was a connection and therefore perhaps this overview made me... it was quite different from the vision I had, for example, at school. (Davide)

According to him, the first difference consists in the degrees of specificity of the problems addressed. Using the metaphor of Branchetti and colleagues (2019), Davide recognizes in the approach adopted for the future-oriented activity the need to look at problems with a “big-eye” perspective, the “generality”, the “overview”, the attitude that makes one say, “let’s consider everything”. On the opposite, for him, the school usually teaches to address much more specific issues. It is interesting his use of the word “model” to identify the “sectoral problems” addressed in a school environment. The idea of model seems connected to the idea of cutting reality, unpacking it in small pieces. But this cut, instead of being valued as an unavoidable step of the modelling procedure to make sense of the world, just gives back the idea that school disciplines are fiction while reality is much more complex and more relevant for them. Later in the interview Davide reflects on the type of problems:

First of all, discuss topics that are not purely scholastic but that turn out to be much more scholastic than the others. So maybe many times we were talking about things that one might think, looking at it from the outside, “These are not strictly related topics” but then they turn out to be much more important than scholastic notions. (Davide)

Here, the issue he addresses is how these problems they studied during the course sound if compared to traditional “scholastic” topics. Actually, he says that these topics “are not purely scholastic” and studying them “from the outside” one could wonder what the connection with school and school disciplines is. However, Davide finds these topics even “much more important than scholastic notions”. This emphasis on the relevance of the issues addressed makes us interpret this sentence as an implicit recommendation he provides to the school system to include real-world contemporary problems in the curricula.

An interesting common aspect between Valeria and Davide is that they both mention the "scholastic notions" as a reference in contrast with the type of knowledge they had put into play to engage with the future-oriented tasks. What is provided from schools seem to them something very local and "sectoral", they compartmentalize reality into small pieces, while the challenges of our societies are global and need to be approached from a different, more holistic perspective. What emerges from their words is a school distant from real world and often unable to teach how to look at the complexity of the present.

4.3.2. Connecting school disciplines

Not only the future-oriented activity but the whole course was a way for the students to meta-reflect on the type of knowledge they had to put into play to reflect on a complex issue and on the disciplinary contributions to address them. For example, Elisa reflects on the novelty of modelling societal problems with scientific tools

> *The more social part of human behavior also struck me a lot. Surely I think it is very complicated to study… because it is more difficult things that do not have many rules. Instead, in reality, you can also do a good job with those to study behaviors and reactions within a society. (Elisa)*

The idea that Elisa expresses is crucial since the course seems to have broken in some sense the barriers between two separate fields: the field of quantity and that of quality. From one side, the scientific disciplines, the reign of the measurable, of the "modelizable", of the things fixed by rules. From the other, the domain of social disciplines that, studying the human behavior, establish a new way of investigating phenomena. Elisa recognizes that the simulations, as transversal methods, are a tool that can help overcoming the boundaries between natural and social sciences, bringing the scientific inquiry in a domain in which she did not think it was possible.
Other students recognized not only a connection between, in general, science and non-science disciplines, but a plurality of ways of addressing a complex societal problem. Valeria for example reflects on her experience within Group 3 and re-reads it in the perspective of disciplinary roles played by herself and her teammates:

> *For example, the idea of immigration was brought it out by Elena, who was in my group. And she spoke of the fact that immigrants in any case could be useful anyway in contrasting globalization. And instead, Paolo saw it more from a technological point of view. That is, he immediately focused on simulation and started working on a simulation while trying to look at the software and change it to adapt it to our requests. So in my opinion they were two different methods of thinking. We thought more about at the, like, theoretical aspect so we thought more by imagining, that is, exploiting the imagination and, if anything, logic, that is, hypothesizing what could happen, and therefore doing like small scenarios each time, and then seeing what they would lead to. Instead, Paolo focused more on, on letting it do to the machine… in the sense, he worked, he put the software and then it is as if he had given the machine the task of giving him the answer. That is, he left the problem to the machine*

by telling it everything that was there, that was part of the problem and then the machine gave us the answer. So, it was precisely these different attitudes that helped us eventually merge the method. (Valeria)

Vittoria recognizes two different ways of reasoning in front of a problem. One consists in reasoning by “logic”, studying the problem in terms of causes, consequences, and future scenarios; the other is a much more technical approach where the obtainment of information about the system was delegated to the simulation. While most of the students reasoned in the first way, trying to develop knowledge about the system by exploring it in logical way, M13 was the only one who tackled the problem by instructing the machine and asking the simulation to return the results. M13 had a strong professional role in the group and was recognized by his colleagues as the expert of computer science and the one who could dialogue with the simulation since, as Valeria says, he “looked at the software and changed it to adapt it to our requests”. However, the fact that there were these different roles was important to create the group’s “method” of inquiry that results to “merge” a plurality of disciplinary attitudes. We can interpret that for Valeria the issue of connection is between disciplines is a matter of what we could call “disciplinary identities” of the members of the group, of how they position themselves with respect to a task, of the “lenses” they are more comfortable to wear to tackle it.

Reasoning about the knowledge and competences coming from school disciplines they had put into play in the future-oriented activity, Jonathan and Giacomo recall ideas more of the history and geography courses rather than of STEM subjects:

However, while we were deciding the problem, the problematic, anyway there, taking into consideration all, all the themes that we could choose. At that point, yes, there was, however, the intervention of scholastic knowledge. So choose something more about the environment then something that they taught us, I don't know, about civic education even at the beginning of the school path with geography. Or for human rights, therefore with history, philosophy. In this case they had been useful but in the end we opted for something different. (Jonathan)

Knowledge of mathematics and physics... oh my, I don't think... during the final project no. From the point of view of the school, in reality, I do not think too many concepts, even if I remember, in the first and second year we did different, let's say... because there is history that becomes history and geography and then we had a teacher who made us do groups in geography and we had to bring different concepts, I don't know... I think that we have studied something about UNICEF and there were others who did UN in general and so on… and therefore, let's say that when we decided to enter and analyze overpopulation, even with international agreements like this, I went to brush them up a bit and I applied them, I don't know, like the 2030 agenda, the goals they set, we studied them like in the second year [of secondary school]. (Giacomo)

In the excerpt, Giacomo says that he did not use competences from mathematics and physics in the future-oriented activity. Actually, as we commented in the sections above, the group performed a very careful analysis of the problem of overpopulation, for example interpreting existing real data and analyzing the time evolution of the population in the different simulated scenarios; however, Giacomo does not recall this as an important “mathematics and physics moment” of the activity and cites the importance of notions coming from courses of geography. He seems to focus more on the specific future-oriented issue addressed rather than on the method used to study this problem.

Following this interpretation, it follows rather straightforwardly that to study the problem of overpopulation are involved more explicitly competences from social disciplines than sciences. However, later in the interview, when asked to reflect on the method of reasoning about scenarios, desires, and actions, Giacomo answers:

> *Ok then as a method... Well then... First of all, starting ... Now I try a moment to analyze so I'm giving an answer but at the same time I'm thinking... we started that we had to focus on a problem and therefore in our case it was overpopulation and then focus on a problem, focus on a problem. We can also encounter it, let's say, as a characteristic during math exercises, because in any case to solve them, obviously also physics, to solve them you have to focus on the problem. And after, let's say, focusing on the problem, we have elaborated, let's say, possible futures, and what are these possible futures? Making a parallelism we could say that the methods we want to use in solving a mathematical problem are, let's say, I don't know... let's start, we focus on a problem, we think, in our opinion, what is the best choice. What is the path to follow in order to arrive at a solution more effectively or more quickly. Then, once we have the solution, we analyze it and then, I don't know, along the way we also add theorems, knowledge, inductions or deductions to arrive at the result. The method, however... the path which, however, is not necessarily always the same, that is, I do not know, in reality it is quite fresh to me as... because today we did the math test and I knew how to do it all, but there was this equation with the exponentials and for some reason not… I had found the solution and the right path. But I was getting a strange result, I don't know like, log3/log2 based on 5/2. Then I deleted everything and I got the illumination and I found the path, an alternative method but the result was ok. And after going to double check the exercise, the first method was not wrong. I simply forgot to write a 2 at one point and then in the end I found it, I did it one way, but I did it right in another too. And so this just reminded me that to get to the solution there is no certainty that there is a single road here. (Giacomo)*

In the excerpt, the student reflects on the overall method suggested by the future-oriented activity and identifies a similarity with the methods of solving problems and exercises of math and physics at school. He recalls the recent experience with a math test in which there was an equation he had solved with a method but, in the end, he found out that also an alternative procedure could be used. The idea conveyed by the module, about for example the existence of multiple possible possibilities, as infinite are the trajectories of the futures' cone, was transposed by Giacomo in a field he is familiar with, within a school discipline like math. He also recognizes the limits of this transposition of the method from the future-oriented activity to the resolution procedure of an equation:

> *In the end, while with the exponentials there is a solution that is that and not another, in working on a problem there is no real solution. It is not certain that the solution you arrive at is wrong, but it is not necessarily the right one either, let's say that there is this freedom from the point of view of imagining and thinking. Which is less, less bound by rules and limits, it is not limited here. (Giacomo)*

Even if there is a similarity in the idea of the different paths that can be done to reach an objective, he realizes that in an exercise of math there is a solution while in a real problem "there is no real solution", meaning that there is not a wrong or right end of the research investigation.

In conclusion, the issue of connection between disciplines is raised by the students in a plurality of different ways. In some sense, they gave a range of interpretations of the same question we asked them: *To tackle this laboratory, did you use knowledge that was provided to you by the school and* *school subjects?* Elisa emphasizes her surprise in front of the connection between disciplines like physics, math and computer science and the world of social phenomena, linked to the methodological approaches that make these issues "modelizable". Valeria sees a connection between the different expertise that emerged during the work in groups: some students reasoned on the model, on its assumptions, exploring it from a "logical" point of view, while others were more comfortable in a much more technical role where the problem was addressed from a computational perspective. Finally, Jonathan and Giacomo recognize that many disciplines need to be considered to deal with future-oriented issues, like history, philosophy, and civic education, but also reason on the possible connections between the methodologies learnt in the scenarios activity to meta-reflect on scholastic issues like the resolution of math or physics problems.

4.3.3. Preparing for future careers

Even if only one student explicitly referred in the interview to the preparation for personal career after school, we thought it was important to stress it anyway. Asked about the take-home message of the whole experience in the course, Valeria answers:

> *Probably as a message, I carry home that... that is, something that may seem simple but in reality there is a world behind it. In my opinion this course has really taught me that, if anything, there is not only the school world, that is, that is… we have always been taught to think in pieces, in the sense, one does primary school, then finishes it, goes to middle school, and then goes to high school, and then chooses the university. In my opinion, on the other hand, we need to start connecting them, that is, we reach the end of our high school, it is true that I am in fourth grade but there is a year left, and in my opinion we need to start a bit to merge things, we need to start dedicating ourselves to the things that really interest us and not every time to look at everything so vastly. In my opinion this course has really taught us that we can start making choices. That is, if one knows what he wants, what he wants to aim for, in case what his interests are, and that is, you can, you can start looking at what can be useful for... That is, to grow those interests. So look at what is needed and what would be the path one should follow, if there is anything that can be useful… (Valeria)*

She stresses the need of focusing in more depth on something that she already sees as her future career. She advocates for a connection of the whole school paths (from primary school to university) with an orientation toward professionalization and career development.

4.3.4. Valuing teamworking as a knowledge building methodology

Another aspect that the students perceived as very important of the future-oriented activity was the fact that it was a group activity. The students enjoyed working with other motivated peers, as Valeria says:

> *it was a group that I enjoyed working with. Because at school it happens instead to be in groups that in case the teacher, if you are good, assigns to you a person who does not want to do anything, and therefore you find yourself having to do all the work alone. Then the work doesn't even come the way you want it, because alone you can't do a job that is supposed to be in a group. And yet in this, that is, in this course there were people who wanted to do... it was not a mandatory thing and therefore in my opinion it was just that, that is, the fact that*

there were people who were interested in the project and therefore they weren't forced to stay there and work, they were people who wanted to discover and work. So in my opinion it was just, it was just what I liked and it was useful for us. (Valeria)

A general appreciation of the team working activity was expressed also by Giacomo who compares the experience in the course with other out-of-school contexts in which he had to collaborate with others in group:

From the point of view of dialogue, then it had already happened to me several times… I don't know, maybe every now and then to break the silence, I don't know, even when I'm out with friends, it happened to talk like this with discussions that maybe came out of nowhere, I don't know… We noticed an aspect of something and then we connected it, maybe one of us, or all of us, to a concept we started talking about like this and this even in different conditions. So yes, dialogue with peers is not strange to me, it had already happened to me many times, collaboration as well. Let's say that I had already collaborated with other guys of my age several times, even in reality, sometimes older, that is, I also did an animation course in the same period as this, in which I had to collaborate with, in fact, guys who were not the same age as me but were in the fifth grade and therefore this recalled me that experience. Yes, let's say collaboration... but, in any case, I believe that collaboration is a really important aspect because in the end it is unity that makes strength, so you have to learn to collaborate. (Giacomo)

Going beyond generical cases of appreciation of the activity, some students, as Davide, underlined the importance of discussing with others in order to carry out the specific tasks:

So... and above all I also liked teamwork. So… discussing, changing my mind, moving forward with others for a common purpose, I really enjoyed it and I will take this as a teaching. (Davide)

As we made explicit in the description of the design principles at the basis of the activity, reasoning in groups on future-oriented topics requires a continue process of negotiation of values in which profound visions of the world are at stake. Davide, in this case, recognized that the activity involved "discussing, changing my mind, moving forward" and that this process was oriented by a "common purpose" which was shared within the group.

Then I am also trying to work a lot on the fact, trying to talk to others, to create a group. […] I liked the fact of reasoning and joining different types of knowledge. There is also the fact that in school we are not always… that is, I always try to combine multiple subjects, to do more subjects, take the various knowledge of the various subjects and then put them together. And I've seen this that was rather useful to me. (Alessio)

Later, in another excerpt of the interview:

So anyway I liked this and you can still interact with different people and meet new people, seeing new ways of working and ways of seeing things has helped me. So it is more stimulating because it is clear that, as long as I think by myself, the things I know are the only ones I can reflect on, but talking to other people, knowledge… I can expand my knowledge on the things I already know. So, I can know more things. (Alessio)

If Davide focuses on sharing a common goal with the other participants, Alessio emphasizes that the members can bring to the group their own knowledge on the topic and putting in common of this knowledge create a set of shared tools and notions that enrich the individual perspectives. He also points out that he felt that for carrying out the tasks of the future-oriented activity he had to "combine multiple subjects, take the various knowledge of the various subjects and then put them together". This observation is strictly related to what we discussed in the previous paragraph on the connection of disciplinary perspectives. We want to underline how, for Alessio, knowledge still comes from school, even when big societal problems are addressed. Knowledge is what disciplines – "subjects" as he calls them – convey and disciplines are still the basis for negotiating complex discussion.

5. Conclusions

In the fourth part study we have seen how the future-oriented activity was for some students an opportunity to reason on the school they desire. While discussing in the groups, in the presentations of their work and also in the interviews, the students pointed out well-known problems that the current organization of school is facing. A thematic analysis has been carried out to identify the main macro-themes which emerged from the presentations and the interviews.

From the analysis of the groups' presentations, we found that the students suffer a great problem of anxiety for their school performance and imagine that this can be mitigated in the school of the future. They see the importance of the role of technology in school innovation but also that no innovation is possible if school knowledge is not re-thought if its times and forms. The students dream about a school as a place for relationships and that can become at the center of the youngsters' routine. Moreover, they recognize the power of their own agency and that of their teachers in the process of school's transformation, and hope that the tragedy of pandemic can be transformed in an opportunity to trigger change. While presenting the ways in which the students raised these issues in the presentations, we discussed the results in the light of the research literature on the mentioned topics.

During the final interviews, the students elaborated more on what is school for them, what are the problems of school learning as it is nowadays, and what should be done to change it. In particular, they would prioritize approaching school learning to contemporary challenges, connecting more school disciplines, preparing for future careers and valuing more teamworking as a knowledge building methodology. In pointing out these issues, the students explained how the future-oriented activity and the module's general architecture helped them in focusing their thoughts and the problematic issues.

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Remarks from Part 3

With Part 3 we have reached the end of the journey of this dissertation, presenting two educational proposals targeted to university Physics and Mathematics students and to secondary school students on simulations of complex systems, whose implementations took place during the third and fourth year of the Ph.D. program. These were very dense chapters, because we dedicated much effort, time, and research investment on the analyses they relate to – respectively about the role of simulations to support decision-making processes and to foster the development of future-scaffolding skills. The richness of the data and the results achieved with both analyses show that computational simulations, if properly addressed, can be a disciplinary ground and a scientifically authentic context to develop decision-making and future-scaffolding skills through science education. However, we believe that the relevance of these chapters is not only for the quality of results achieved but for the detailed description we provided of the modules in which we implemented the educational reconstruction of the contents developed in Part 2, especially for what concerns the way to present models and simulations, to discuss the code implementation and the assumptions at their basis. Moreover, also in writing the chapters we tried to reconstruct all the steps that conducted us to the modules' design, including preliminary experiences and background studies. A Ph.D. journey is a non-linear story of failures and successes, of great enthusiasms and routine work: we tried to recall, remember, and consider most of these moments in the writing phase too.

The two studies of Part 3 that conclude this dissertation allowed us to:

- present two teaching-learning modules and several innovative activities on computational simulations addressed to two different target groups (university Physics and Mathematics students and high school students);
- show how simulations of complex systems, and in particular agent-based simulations, can support the development of decision-making and future-scaffolding skills, which are both important competences to foster students' agency;
- conceptualize authentic computational simulations as complex interdisciplinary objects that embed a variety of forms of knowledge representation;
- understand that students can be guided to grasp the role of agent-based "toy" simulations to think about societal real-life issues;
- investigate on the ways in which simulations can be used to develop future scenarios;
- point out that properly designed future-oriented activity can be lived by the students as "free thinking spaces" to discuss about the problems of school in the present and dream about their desirable school of the future.

Appendixes

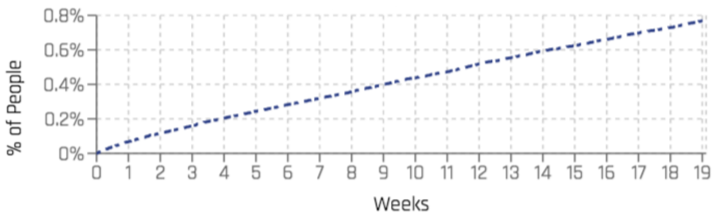
Appendix A – Protocol of the individual interviews

<u>Problem formulation and analysis</u>

Imagine that you are a mayor of a town of about 20,000 inhabitants. One day a letter from the secret services arrives at your desk informing you that a terrorist group has recently formed in your town and that it appears to be expanding. In five months, the group has grown to 20 people. It is the first time that a phenomenon of this kind has occurred in your town, and you are certainly worried.

- How could this have happened?

You ask the intelligence for an explanation. They send you a file containing data on the trend in the number of people of this terrorist group. They provide you with this graph:



- How do you interpret it? Does it suggest a mechanism in the formation of the terrorist group? Beyond the reasons for "why" a terrorist group was formed (e.g. discontent with your decisions as mayor, distrust of institutions), can you see "how" this was formed? Can you see a "story" of this group?

Still shocked by the news, after thinking about the possible causes of this phenomenon, you think about what a way could be to deal with this emergency.

- What do you propose to do as mayor?

You decide to bring together the municipal council and put three possible intervention ideas on the table:
<u>Employment</u>: incentivizing employers to hire at-risk individuals.
<u>Social workers</u>: increase the number of social workers who favor the involvement of individuals at risk in social activities.
<u>Community police</u>: Increase the number of specially trained community police officers, to change the role and effect of police officers in the community, reducing the number of negative interactions between citizens and police.

- Are you able to believe that these options are effective? And that there is one more effective than another? Based on what?
- Would you ever use a computer to make a decision? Do you think it is possible to simulate the process of forming terrorist groups? How would you do it? Would it be reliable? Could you use it to make decisions for your community?

<u>Exploration of the "expert" model</u>

A few days after the meeting, the leaders of anti-terrorism intelligence contact you to introduce you to a work done by researchers who deal with modeling complex social phenomena. This is the first part of the report, which describes the model they used:

We developed an agent-based model with the aim of examining what types of interventions would reduce radicalization and recruitment into terrorism. The time scale of the model is six months and each phase of the model represents one hour. The behavior of individuals is modeled as heterogeneous agents that have certain characteristics that make them at risk of radicalization. These are:

- *Some socio-demographic characteristics such as gender, age, employment status, criminal record and authoritarian personality*
- *Some cultural characteristics related to topics such as: the perception of integration in society, trust in institutions, the subjective condition of social advantage / disadvantage. In fact, an accurate reading of the literature has made it possible to identify these three topics as particularly significant in the dynamics of recruitment.*
- *A routine, determined by socio-demographic and cultural characteristics which, in turn, determines socialization patterns through interactions between individuals both in person and online.*

When the risk of radicalization reaches a certain threshold, individuals can be recruited. Recruitment in the terrorist group occurs after interacting with specific figures, the recruiters, in specific places for a specific period of time. The model measures three main outcomes, the number of individuals recruited, the number of radicalized individuals, and cultural characteristics based on opinions on the topics identified.

- Do you have any comments to make about this model? Has your initial idea about why terrorist groups are formed has changed? If so, how?

<u>Exploration of a small problem on the expert model</u>

To reason together on the proposed model, the intelligence leaders organize a workshop for you and your city council to think about the theoretical foundations of the model. In particular, reflect on the so-called "opinion dynamic", used to describe how people, interacting, change their opinion or not, approaching or not the "recruitment threshold". From sociological analyses, it has been highlighted how interactions take place between people who share, at least partially, some opinion and that, in the interaction, the opinions only get closer - they never move away - causing the two individuals to become more similar.

- Does this type of modeling of the exchange of views make sense to you? If not, why?
- If, however, the trend is towards an approximation of opinions, how can it happen that two groups of people with very different opinions are created in a city or society? How do you organize yourself to answer this question?
- If you wanted to answer through a computer simulation, what would you do?
- A simulation implementing this model is available on Netlogo [the student opens the simulation (Barelli, 2021, sim)]. Do some experiments. Does it help you answer why there is a polarization phenomenon?

<u>Exploration of the three scenarios with the simulation</u>

Using the data of your town (number of inhabitants, distribution by age, profession, unemployment rate, ...), the same researchers have created a computational simulation to explore the effectiveness of employment policies, increase of social workers and agents of community police: http://193.142.112.115:8020/intervention

- What do you extract from these graphs? Are they easy to read? What do you read in them?
- The simulation shows us that the increased employment policy has reduced the number of people affiliated with terrorist groups, while this does not happen by adding social workers or specialized policemen. Why, in your opinion?
- Does the simulation help you tell why one intervention "works/might work" and others don't?

- Going into the details of the model, the "employment" scenario acts by reducing the time and the likelihood of coming into contact with recruiters, the "social workers" scenario acts by promoting trust and integration and reducing subjective feelings of deprivation, “community police” scenario acts by reducing negative interactions between individuals at risk and law enforcement agencies and, similarly to the previous scenario, it promotes integration and trust and will reduce feelings of deprivation. This helps you, along with the simulation, to say why one intervention “works/could work” and others don't?
- Do you trust this simulation? As mayor of your town, would you be guided by this simulation to decide which line to take? How would you justify using this tool to your citizenship?

Concluding questions

We have reached the end of the interview.

- Have you ever seen a simulation like this of terrorism? If so, in what context? Did it expand your idea of what a simulation is today? Do you think it may be important to also examine simulations of this type during university courses in physics or mathematics?

Appendix B – Description of the roles of the role-play activity

Role	Description
Public order responsible	You are the responsible for public order in a town, which we will call Xitta, of 20,000 inhabitants. From an early age you always knew what you wanted to do. You've been through all the ranks: the military for years, the competition to enter the *Carabinieri*, many years of service, and finally you have what you deserve: an authoritative position. You are now in charge of organizing the police forces on the territory of Xitta. For you, Xitta's safety comes first and you are convinced that having a hard pulse always leads to the solution of all problems. Recently, to reach the mandatory number of hours for in-service training, you are attending refresher courses on psychological aspects of conflict resolution within heterogeneous communities. Current situation: Lately there has been a wave of vandalism in the city that you have managed, in your opinion, very well.
Social integration advisor	You are councilor for social integration of a town, which we will call Xitta, of 20,000 inhabitants. You have Arab origins, your parents moved to Italy to look for a better future, you were born and raised in Xitta, you know how important the dialogue between different ethnic groups and religions is. In the village there are small Muslim, Jewish, Protestant communities and so on. You deal with social assistance, equal opportunities, cultural initiatives that facilitate coexistence between different traditions. You have made a political commitment to prevent others, like you in the past, from feeling marginalized. The mayor is still a bit skeptical about your role: you would have many good ideas and, although you are not given enough funds, you still have the feeling that you listen. Current situation: In this period, you are dealing with a group of Kurds who have recently arrived in Xitta after fleeing the war. They have every intention of integrating into the life of the town and we care that this transition is managed in the best possible way.
Tourism, culture and events advisor	You are councilor for tourism, culture and events of a town, which we will call Xitta, of 20,000 inhabitants. You have a long history of PR and of organizing cultural clubs, literary cafes, demonstrations, artistic events. You were able to grasp Xitta's potential by returning from a trip to an island in Greece, you have seen its similarities, and now you are using all your energy so that your country can enjoy an attractive image from a tourist point of view. Every now and then you feel frustration, you are forced to organize village festivals and other folkloristic events, because the population, in your opinion, is not yet sufficiently literate, therefore it does not rise, it would not appreciate more chic events. A city still too "popular", but you are confident, you will make it. Current situation: An important traveling festival has set one of its stops in Xitta. You finally have your chance. You have a good season of events in mind, and you absolutely don't want your project to be ruined.
Urban planning advisor	You are city planning councilor for a town, which we will call Xitta, of 20,000 inhabitants. You take care of the conditions of the common green, of municipal buildings such as schools and offices, of squares and streets. You have a good relationship with the mayor, you are the oldest in council, he listens to you willingly, he trusts your skills, after all you are an engineer. You get the feeling that he never gives you all the funds you would need to do a great job, but you always get by. Only one thing you can't stand: vandals, when they destroy something, you always think twice before fixing it. Current situation: You have just received a socio-economic mapping of the city's neighborhoods following a survey that reveals the places of greatest aggregation of the Xitters. Note that a peripheral area is being repopulated due to migratory phenomena.
Scientific development advisor	You are councilor for scientific development of a town, which we will call Xitta, of 20,000 inhabitants. You have a degree in Physics and have a strong interest in the study of mathematical models, complex systems and simulations. You have deep faith in technology and science, the

	mayor appreciates your expertise, and luckily! Unfortunately, he cannot help but listen to other opinions from the junta, but you are firmly convinced that these others can boast of only one characteristic: arrogance. You know very well that having taken some math exam, such as analysis 1, analysis 2, etc. it does not really form anyone. You are aware of the power of the sciences. One of the few who know how to master so much wisdom. Current situation: Lately your studies have focused on a simulation of the Axelrod model and you can't wait to find an application of this model to real contexts to understand how far the model can lead
Councilor (1)	You are municipal councilor of a town, which we will call Xitta, of 20,000 inhabitants. You were born and raised in the suburbs of the town, your family has handed down the fruit and vegetable cart and the consequent business for generations, from father to son. However, it has never been easy to make ends meet. In the neighborhood where you live, known as “the Palazzoni”, you were still among the luckiest, you had a job, other families were worse off. So, at a certain point, you decided to run for councilor, in order to bring the needs of the periphery to the attention of the institutions, and in fact you were elected. You are not very educated, but with words you know how to assert yourself anyway, the mayor takes you into consideration. Current situation: Your people have told you that in the last period the condition in the high-rise buildings is even worse, also due to the strikes of the workers protesting the working conditions and the recent layoffs.
Councilor (2)	You are municipal councilor of a town, which we will call Xitta, of 20,000 inhabitants. You were born and raised in Xitta and you are a primary school teacher, close to retirement. For your work with children, you have always been an expert in settling disputes, from the most trivial to the most serious. You have always been interested in the public cause. In recent years you have noticed a climate of growing tension between the political factions in your town and this thing deeply distressed you. You joined Facebook and in the Facebook group “You are from Xitta if...” you have shown your greatest gift: to lead users to listen to each other and to think, finding points of agreement even when it seemed impossible. Right on Facebook the candidate for the civic list noticed you and asked you to support him in his race for mayor. You were hesitant to expose yourself in this way, but you accepted and now, in the city council, you usually mediate between the opinions of the members of the junta. Current situation: On the Facebook group, which you continue to monitor assiduously, the Xitters are having a lively discussion on the recent vandalism that took place in Xitta and on the protests of workers in the Palazzoni district. As always, you are doing your best, but it is not an easy situation.

Appendix C – Protocol for the role-play activity – version for facilitators

Introduction

The facilitator of the role-play activity, once the call with the working group has begun, will explain how the activity will take place.

In private chat, each participant will be assigned a "profile", a sort of character sheet, randomly. The members will be given the "task" to enter the role. The game is designed for a minimum of 1 player (but it would be like returning to the individual interview), to a maximum of 6 players, excluding the mayor, who must be interpreted by the Facilitator. It is important to underline that following every characteristic of the character in the letter is not mandatory, free interpretation is welcome, what is most important is that everyone feels at ease.

The goal of the individual player is to convince the mayor, through arguments, motivations, and dialectics, to make decisions in line with their psychological profile.

Introduction of the characters

Once the roles have been assigned to all members, the game begins. The Mayor/Facilitator illustrates the setting:

We are in Xitta a town of 20,000 inhabitants, I am the Mayor and you are my municipal council, I have gathered you all together because I need your help to manage and solve a very serious problem. Because of the gravity of the situation, I have summoned you all, even those who are usually not present at the board meetings. For this reason, before starting, I propose to each of you to introduce themselves briefly, also updating me on any news regarding the sectors of your competence.

Each councilor introduces him/herself briefly, illustrating his/her role in the council and the current situation regarding the sphere of his/her competence. [time foreseen: 5 minutes]

Statement of the problem

But let's get back to why I summoned you. The secret services sent me this email.

The Facilitator sends the following message in chat:

> *Sensitive communication:*
> *A terrorist group has recently formed in Xitta and appears to be expanding. In five months, the group has grown to 20 people. One may wonder how it could have happened, what are the reasons, what order of magnitude it is. We will continue to investigate also taking into consideration that we had never encountered such movements in the city until now. That's all for now.*
> *Signed*
> *Xitters secret services.*

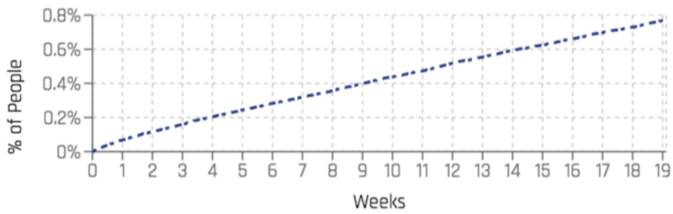
The group can start discussing it. [time foreseen: 10 minutes]

Introduction of the graph

When they have supposed reasons and type of trend, the Facilitator will intervene again:

I just received another e-mail: a dossier containing data on the trend in the number of people of this terrorist group. They gave me this graph:

The facilitator sends the image via chat.



You have to help me understand how to interpret it. Beyond the reasons for "why" a terrorist group was formed, can you see "how" this was formed? Can you see a "story" of this group?

The group is left to discuss a little more. ATTENTION: Here it is crucial to arrive at a hypothesis of a mechanism on the formation of the terrorist group. How is recruitment done? (Although this word is not named) Are people recruited all together? Is it a recruitment that spreads by word of mouth from person to person, "like a virus"? What does this linear graph mean? [time foreseen: 10 minutes]

<u>Proposal of possible interventions</u>
We are offered these types of intervention to deal with the emergency.

The facilitator sends a message to the group via chat.

> *Community police, i.e. increasing the number of specially trained community policemen, to change the role and effect of police officers in the community, reducing the number of negative interactions between citizens and police*
> *Social workers, that is to say increasing the number of social workers who favor the involvement of individuals at risk in social activities*
> *Employment, or to encourage employers to hire individuals at risk.*

What would you advise me to do?

At this point a private message is sent to a member of the city council:

> *You have been corrupted by the terrorist group. Being careful not to get caught, try to boycott any dominant idea by highlighting the aspects that may not work*

In this phase the "game" will be in trying to convince the Mayor to make one of the three decisions. ATTENTION: Try as much as possible to choose only one solution, to facilitate discussion and debate. Only at the end will there be the possibility to propose an intervention on several options. [time foreseen: 30 minutes]

Presentation of the agent-based model
Now the secret services are asking me if we would ever use a computer to make a decision. Would you like to use a simulation to make decisions for your community? Is it possible to simulate the process of forming terrorist groups? How would you do it? Would it be reliable?

The group can discuss it a bit

Researchers who deal with modeling complex social phenomena present us with a work. This is the first part of the report, which describes the model they used. Please watch the chat.

Facilitator writes on meeting chat the following message:

We have developed an agent-based model with the aim of examining what types of interventions would reduce radicalization and recruitment into terrorism. The time scale of the model is six months and each phase of the model represents one hour. The behavior of individuals is modeled as heterogeneous agents that have certain characteristics that make them at risk of radicalization. These are:
- Some socio-demographic characteristics such as gender, age, employment status, criminal record and authoritarian personality
- Some cultural characteristics related to topics such as: the perception of integration in society, trust in institutions, the subjective condition of social advantage / disadvantage. In fact, an accurate reading of the literature has made it possible to identify these three topics as particularly significant in the dynamics of recruitment.
- A routine, determined by socio-demographic and cultural characteristics which, in turn, determines socialization patterns through interactions between individuals both in person and online.
When the risk of radicalization reaches a certain threshold, individuals can be recruited. Recruitment in the terrorist group occurs after interacting with specific figures, the recruiters, in specific places for a specific period of time. The model measures three main outcomes, the number of individuals recruited, the number of radicalized individuals, and cultural characteristics based on opinions on the topics identified.

The group has time to read.

What do you think? Does it convince you?

The group can discuss it a bit. ATTENTION: guide students to recognize the different planes of what the model takes into consideration (socio-demographic aspects, opinions, routines). It would be interesting if the group reflected on how these elements of the model can be modified or not by the proposed interventions. If the scientific development advisor does not intervene by proposing Axelrod, the mayor could encourage him by saying for example "*Doctor XYZ, you phoned me the other day to talk to me about this model you were so enthusiastic about... do you find it useful in this situation? Can you tell us about it?*"* [time foreseen: 40 minutes]

Based on the model, what is the definitive solution we propose?

The students can vote. At this point it is also allowed to have a combination of options.

Appendix D – Questionnaires for the activity of lesson 4

Wolf sheep predation

Let's tackle the problem of the disappearance of small businesses in favor of large companies, franchising, online giants through the NetLogo “wolf sheep predation" simulation: what do the various elements of the simulation correspond to in the real problem?

Name and surname: __________________________

Wolves:

Sheep:

Grass:

Mechanism of predation:

Initial-number-sheep and initial-number-wolves (initial number of sheep and wolves):

Grass-regrowth-time (time needed by grass to regenerate):

Sheep-gain-from-food and wolf-gain-from-food (energy gained by sheep and wolves when they eat):

Sheep-reproduce and wolf-reproduce (probability of sheep and wolves to reproduce)

Other analogies or differences that you see between the simulation and the real problem:

Voting

Let's face the problem related to the fact that, on social networks, we are exposed to news and information that reinforce our opinions (phenomenon of "echo chambers"): what do the various elements of the simulation correspond to in the real problem?

Name and surname: __________________________

Green agents:

Blue agents:

Influence:

Agents’ color:

Change-vote-if-tied? (in case of a tie among the colors of neighbors, the central agent changes its color):

Award-close-calls-to-loser? (if 5 neighbors are of a color and 3 of another, the central agent takes the color of the minority):

Final configuration:

Other analogies or differences that you see between the simulation and the real problem:

<u>Cooperation</u>

Let's face the problem related to the fact that, in the face of the climate emergency, lifestyles more or less ecologically oriented can be adopted: what do the various elements of the simulation correspond to in the real problem?

Name and surname: __________________________

Greedy cows:

Cooperative cows:

Grass:

Grass' consumption:

Modality of grass' consumption by greedy cows:

Modality of grass' consumption by the cooperative cows:

Reproduction-cost (energy lost by a cow when it reproduces):

Grass-energy (energy gained by a cow when it eats):

Threshold of grass' growth (below this threshold, the grass grows more slowly):

Other analogies or differences that you see between the simulation and the real problem:

Appendix E – Guide to the future-oriented activity

Step 1 - identify the problem

Duration: 30 minutes

Task: Pick an issue that you feel urgently today and would like it resolved in 2040. The problem can concern any context: your schools, your city, Italy, Europe or the whole world.

Each member of the group proposes a problem of interest to him and discusses everyone's proposals, then voting for the most convincing one.

At the end of the discussion, write here the problem you have identified, explaining the context you are referring to:

Phase 2 - exploration of different possible futures

Duration: 30 minutes

Task: Getting inspired by the simulation you think is most suitable, explore possible evolutions of the problem from the present to the future and imagine what scenarios you could arrive at in 2040.

Briefly describe at least three alternative future situations that the simulation inspired you:

Phase 3 - imagining a desirable scenario for 2040

Duration: 1 hour

Task: Now imagine that in 2040 the problem you have selected has been solved. Describe in as much detail as possible your desirable scenario for 2040. Include in your description the stakeholders, the interests at stake, how life unfolds in the context in which you are located, the elements of novelty and those of continuity with respect to the past. At this stage... dream! Throw your imagination beyond the obstacles of the present!

As you enrich your scenario, describe it here, along with the elements that characterize it:

Phase 4 - back-casting: from the future to the present

Duration: 1 hour and a half

Task: Starting from the desirable scenario, think about what actions, decisions, policies, contingencies made it possible to reach the realization of that ideal future in 2040. Were there any bifurcations, moments of uncertainty? What role did the various stakeholders play?

Use this space to write down the most significant passages of the timeline:

Step 5 - tell your success story

Duration: 120 minutes

Task: Prepare a 10-minute presentation to do during the last meeting (Tuesday 23 February) to tell everyone your success story of which you were the agents, the protagonists. To do this, decide on a name for your group with which to introduce yourself to others, give yourself a role in the story and develop a presentation method (a story, slides, a video…). In the presentation, highlight in particular the role that simulation has played for you in analyzing the problem, imagining the scenarios and creating your success story.

Appendix F – Final standardized evaluation questionnaire[22]

<u>Consent form</u>

Dear student,

we have prepared this final questionnaire, which aims to increase the ability to guide students towards the future choice and to express the satisfaction and effectiveness of the experience.

We would like to inform you that the questionnaire is totally anonymous and the identification of the single person associated with a single response form will not be possible or admitted by virtue of the regulations in force in accordance with art. 89 Regulation n. 679/2016 and art. 100 Legislative Decree n. 196/2003.

If the results emerged were used for scientific research purposes, for example the publication of articles in academic journals, they would be presented in aggregate and anonymous form, in order to guarantee the privacy of the participants.

It is very important that you answer the questionnaire in every single part.

The data controller is UNIBO AFORM in the person of Daniela Taccone. Responsible for the protection of personal data is the Department of Education "G. M. Bertin" in the person of Dina Guglielmi. If in doubt, you can contact us at daniela.taccone@unibo.it or dina.guglielmi@unibo.it or at the telephone number 051 2091623.

The data will be stored by the owners, in accordance with the principles set out in art. 5 EU regulation 2016/679, for a period of time not exceeding the achievement of the purposes and with specific regard to the conservation limitation principle referred to in art. 5, letter e), EU regulation 2016/679. From the scheduled conclusion of the research, the data will be kept confidential for five years (Provision of the Guarantor n. 2 of 16 June 2004 art. 3, Official Gazette 14 August 2004, n. 190).

You have the right to ask the data controller (daniela.taccone@unibo.it) for the following:

- access to personal data governed by art. 15 of EU Regulation 679/2016;
- the rectification or cancellation of the same or the limitation of the processing provided for respectively by articles 16, 17 and 18 of EU Regulation 679/2016;
- data portability (law applicable only to data in electronic format) governed by art. 20 of EU Regulation 679/2016;
- opposition to the processing of their personal data pursuant to art. 21 of EU Regulation 679/2016.

Thanking you for your cooperation, we send our best regards.

Having read the information, we ask you to indicate whether you consent to the processing of your data for statistical and scientific research purposes:

□ I consent

Name:

Surname:

E-mail address:

Gender: Male / Female / Indefinite or in transition

Institute:

Grade: 3 / 4 / 5

Host department:

Indicate the laboratory you participated in within the Department of Physics and Astronomy:

- Laboratory 1: Electrons and Photons from atoms to solids
- Laboratory 2: Big data and networks between physics and biology
- Laboratory 3: Simulations of complex systems
- Laboratory 4: Climate Change
- Laboratory 5: Workshop-laboratory

[22] Questionnaire provided by the orientation unit of the University of Bologna.

Campus: Bologna / Cesena / Forlì / Ravenna / Rimini
Duration of the activity you took part (in hours):

Compared to the initial expectations, to what extent do you think the concluded experience has satisfied them?

	Not at all	A little	Rather	A lot	Complet ely
Strengthen theoretical knowledge learnt at school	○	○	○	○	○
Acquire technical-practical competences	○	○	○	○	○
Orient toward future choices	○	○	○	○	○
Favor the knowledge of the university context	○	○	○	○	○

Do you want to add some comments about it?

How much do you think this experience has helped you to...

	Not at all	A little	Rather	A lot	Complet ely
Reflect on your personal characteristics (who are you)	○	○	○	○	○
Reflect on your abilities (what you are able to do)	○	○	○	○	○
Reflect on your interests (what you like to do)	○	○	○	○	○
Understand your expectations about the choice you will have to make	○	○	○	○	○

We ask you to give an assessment of some aspects of the content of the accompanying training[23] (online). The training...

	Not at all	A little	Rather	A lot	Complet ely
Was clear	○	○	○	○	○
Was interesting	○	○	○	○	○

[23] Before the beginning of the lesson of the module, the students participated to an activity carried out by the unit of the University of Bologna that is in charge for the university orientation.

Was coherent with the project	○	○	○	○	○
Was useful for the following activities	○	○	○	○	○

To what extent the main activities carried out were:

	Not at all	A little	Rather	A lot	Completely
In line with your interests	○	○	○	○	○
Adequate to your school level of knowledge	○	○	○	○	○
Coherent with your school path	○	○	○	○	○
Useful for your personal growth	○	○	○	○	○
Useful to understand the knowledge of the university context	○	○	○	○	○

The knowledge and skills you possess, compared to the experience carried out, are: Greater than requested / Adequate / Lower than requested

To what extent has the support provided by the tutor been useful to you in carrying out your activity? (answer only if there was the presence of a tutor) Not at all / A little / Rather / A lot / Completely

Explain your answer (answer only if there was the presence of a tutor)

Did you encounter any difficulties during the experience? Never / Rarely / Sometimes / Often / Always

If you have encountered difficulties, what type were they? Relational / Connected to the tasks / Connected to the amount of work / Connected to organization of times and places

The duration of the experience resulted: Too short / Adequate / Too long

How are you satisfied with the experience? Not at all / A little / Rather / A lot / Completely

Explain your answer (answer only if there was the presence of a tutor)

Would you recommend this experience to a friend? Yes / No

In your opinion, was this experience useful for university orientation? (choose the option you agree with most)

- Yes, it increased my interest in science
- Yes, I understand that I have many job opportunities after a possible degree in the explored field
- Yes, I was intrigued by the experts' decisions about their experiences
- Partly yes and partly no, because I already know what I want to do but it is so broad that it is difficult to understand my path
- No, I have not changed my future idea

Why was it useful in your opinion?

- It gave me a different perspective
- It gave me new insights to think about, including on courses that I would not have considered before
- It made me consider new university faculties

Why wasn't it useful in your opinion?

- I had already intended to attend a degree course belonging to the field explored
- I am already oriented towards something else

Please read the following statements carefully and indicate how confident you are in your ability to perform each of them according to the following scale:

	Not confident at all	Slightly confident	Somewhat confident	Fairly confident	Completely confident
Select a professional field among those you might consider	○	○	○	○	○
Select a specific profession from those you might consider	○	○	○	○	○
Choose a profession that fits the lifestyle you prefer	○	○	○	○	○
Deciding which profession to carry out and then no longer worrying about whether it is the right or wrong one	○	○	○	○	○
Choose a field of study or a profession that is in tune with your interests	○	○	○	○	○
Identify some reasonable alternatives regarding your education or profession if you have difficulty making your first choice	○	○	○	○	○

Find information about the professions that interest you	◯	◯	◯	◯	◯
Find out about employment opportunities for a job over the next ten years	◯	◯	◯	◯	◯
Identify the average annual salaries that are received in the context of a given profession	◯	◯	◯	◯	◯
Talk to a person already employed in the professional field / course of study that interests you	◯	◯	◯	◯	◯
Identify employers, companies, institutions that are important for your possible professional occupation	◯	◯	◯	◯	◯
Find information on possible degree courses or professions	◯	◯	◯	◯	◯
Make a thorough analysis of your skills	◯	◯	◯	◯	◯
Focus and specify your ideal profession	◯	◯	◯	◯	◯
Continue to persist to achieve your professional or educational goal even if you encounter failure	◯	◯	◯	◯	◯
Decide what is most important to you in a business occupation	◯	◯	◯	◯	◯
Understand how much you are ready to sacrifice to pursue your professional goals	◯	◯	◯	◯	◯

Define the lifestyle you would like to have	○	○	○	○	○
Make a plan for achieving your goals for the next five years	○	○	○	○	○
Identify the steps to take if you encounter difficulties in a chosen professional sector (or in the chosen course of study)	○	○	○	○	○
Identify the steps required to successfully complete the chosen training path	○	○	○	○	○
Properly prepare a curriculum vitae	○	○	○	○	○
Change your career if you find that you don't like your first choice	○	○	○	○	○
Change employment if you are not satisfied with the one undertaken	○	○	○	○	○
Successfully manage a job interview	○	○	○	○	○

Following the experience carried out, thinking about the university choice...

- I understood that this is the right area for me
- I understand that this area interests me, but I still want to explore alternatives
- I understand that this area does not interest me

Compared to the 16 fields to which the University of Bologna degree programs presented to you refer, which are you interested in?

- Economy and management
- Pharmacy and biotechnology
- Law
- Engineering and architecture
- Languages and Literatures, Translation and Interpretation
- Medicine and Surgery
- Veterinary medicine
- Psychology

- Science
- Agro-food sciences
- Education and training sciences
- Exercise sciences
- Political sciences
- Statistical Sciences
- Sociology
- Humanities studies

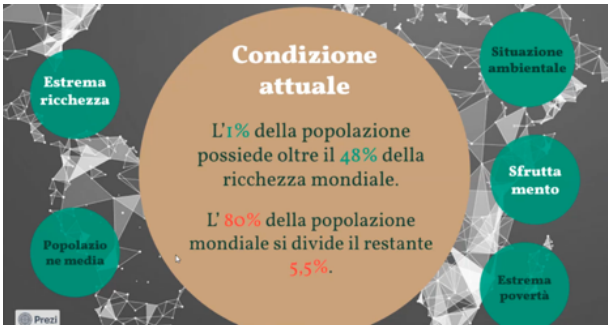
Thank you for completing the survey.
The response was recorded.

Appendix G – Transcripts of the groups' presentations with codes for future-scaffolding skills

Group 1 – The Sims (M1, F2, M3, M4, M5)

M4

18:25 Ok allora il problema che abbiamo affrontato noi era la distribuzione mondiale della ricchezza e di tutte le risorse. Per partire abbiamo cercato di schematizzare in un percorso. Quindi siamo andati ad esaminare il contesto attuale, la simulazione che abbiamo utilizzato ci ha aiutato sia per capire il nostro contesto che per dare delle risposte, e poi le soluzioni che adotteremo [St4]. Partiamo dalla condizione attuale. Qui ci sono alcuni dati che ci fanno capire come sono distribuite le ricchezze.



19:14 L'1% della popolazione mondiale che possiede il 48 per cento della ricchezza. E poi questa sarebbe la parte più ricca. E poi abbiamo una parte anche più povera di cui fa parte l'80% della popolazione che dispone però solo del 5,5% delle risorse. E quindi questo significa che nonostante noi stiamo vivendo in uno dei periodi con forse il periodo con più ricchezza su questo pianeta in termini materiali c'è anche un grave problema di distribuzione. In questa slide siamo andati anche ad esaminare quelli che sono i vari punti che noi tocchiamo. Quindi avremo delle zone di estrema ricchezza, come per esempio in questa foto c'è Dubai cioè dei punti geograficamente molto piccoli però dove è detenuta un'estrema quantità di ricchezza.

Poi abbiamo una popolazione media che fortunatamente è abbastanza grande. Questa popolazione media vive soprattutto in Nord America e in Europa. E un dato però molto preoccupante è che questa popolazione media è alla base del consumismo, alla base degli sprechi ed è la macchina che consuma tutto.

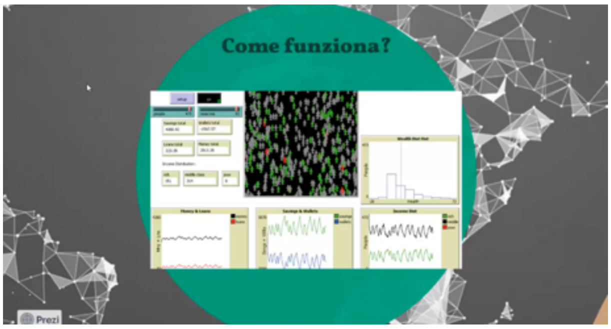
Un dato scioccante è che un terzo del cibo che viene prodotto è sprecato. Questo ci fa capire la portata anche degli sprechi. Oltre ad esaminare i vari contesti in cui vive la popolazione bisogna anche vedere dei problemi ulteriori che questa situazione sta portando [St4], che questa disuguaglianza sta portando. In questo caso la situazione ambientale. C'è Nell'Oceano Pacifico un'isola di rifiuti che secondo le stime è grande un'area compresa tra la penisola iberica gli Stati Uniti d'America. Questo ci fa capire quanta è la portata di rifiuti che stiamo consumando e ci fa anche capire quanto questa società sia consumistica nel vero senso della parola, nel termine più duro, cioè consumare le cose nel minor tempo possibile.

Quindi questa situazione porta anche degli aspetti negativi. Abbiamo visto gli aspetti positivi [St4] come l'estrema concentrazione di ricchezza oppure una buona parte della popolazione che vive in una condizione comunque agiata. Abbiamo però chi sostiene tutto questo sistema che tante volte sono anche delle persone in condizioni precarie e che sono di fatto sfruttate per il loro lavoro però che servono come macchina per far andare avanti i proprio che sostiene questo sistema.

E poi abbiamo anche la parte più triste che è l'estrema povertà della popolazione un dato drammatico e che al mondo ogni giorno 20.000 persone muoiono di fame e di stenti. E questa è una situazione drammatica anche soprattutto per la morte ma anche perché come abbiamo visto prima c'è una parte della popolazione che un terzo del cibo lo spreca mentre altre parte di popolazione che questo cibo non c'è affatto.

Quindi la drammaticità non sta tanto nel "Questo sistema non funziona perché non c'è abbastanza" ma "questo sistema va bene però è distribuito in maniera sbagliata". Questa era la contestualizzazione del sistema.

Ora andiamo a vedere la simulazione che abbiamo fatto. Abbiamo utilizzato una simulazione cash flow cioè ci siamo domandati di fatto la ricchezza che noi l'abbiamo espressa in termini monetari, come gli istituti bancari influenzano la distribuzione della ricchezza? E soprattutto come varia a ricchezza mondiale in funzione della quantità di riserva della banca? Cioè se ci sono degli istituti bancari forti questo farà cambiare l'assetto della distribuzione della ricchezza? Andiamo a vederlo meglio [St2].



Qua è una schermata su come funzionano ma come funziona la simulazione sul display abbiamo un numero di persone in questo caso abbiamo settato a molto alto 473 perché ipotizzando un orizzonte temporale lungo abbiamo ipotizzato che ci fossero tante persone sul pianeta e questo sistema ci fa vedere: mentre questi omini interagiscono sia fra di loro che con la banca, cosa succede? Gli aspetti più importanti sono: l'income distribution cioè quante persone ricche, quante persone di media classe e quante persone povere ci saranno. Un altro aspetto cardine sono le reserves. Cioè le reserves sono le riserve che si hanno in banca. Cioè di tutta la moneta circolante, quanta effettivamente è depositata nei conti della banca. E poi lei con queste riserve andrà a gestire tutta la produzione. Andiamo a vedere quindi come variano la ricchezza o meglio la distribuzione della ricchezza in funzione delle quantità di riserve nella banca.

Quando avremo degli istituti bancari deboli, quindi persone sempre uguali tanti però le reserves poche, 14. In questo caso abbiamo una grande popolazione ricca una grande popolazione povera e una classe media molto snella. Questo significa che se gli istituti bancari hanno poche riserve ci sarà una classe media piccola e soprattutto molta differenza: il numero delle persone ricche e delle persone povere è molto più alto.

Se invece abbiamo una riserva media quindi abbiamo aumentato con questo cursore le riserve, abbiamo visto che la classe media diventa più grande. Le persone ricche sono comunque in buona proporzione. Abbiamo però una diminuzione sostanziale delle persone povere e questo ci porta sulla buona strada e ci fa capire quanto questi sistemi bancari possano influenzare la distribuzione.

E poi abbiamo ovviamente delle reserves alte. Se la moneta mondiale è trattenuta in un organo centralizzato e le riserve di conseguenza sono molto alte, abbiamo una classe ricca che è comunque presente, c'è una grande maggioranza della classe media come dovrebbe essere e soprattutto, la cosa più importante, abbiamo una classe povera poco, molte poche persone ci sono.
Cosa ci è servito questa simulazione? Questa simulazione del cash flow ci è servita oltre a capire come funzionano anche i sistemi moderni finanziari. Ci è servita a capire come noi possiamo fare per riuscire a rendere più distribuita la ricchezza. E da questa simulazione abbiamo capito che bisogna riuscire a creare un organo centralizzato molto forte molto potente. Solo così si riuscirà ad avere una distribuzione abbastanza omogenea. Una volta quindi che la simulazione ha fatto vedere quali sono le possibili soluzioni che abbiamo e quali sono i possibili mondi che potremo avere a seconda della forza degli istituti Bancari, Andiamo a vedere le soluzioni che abbiamo adottato.

Nella nostra situazione desiderata, la ricchezza appunto è detenuta da un organo mondiale esecutivo a rappresentanza popolare. Non si genera più produzione per consumo ma si genera una produzione per appagamento dei bisogni. Quindi la produzione si placherà una volta che i bisogni vengono placati. Abbiamo un benessere che è molto dell'intera comunità, non di una buona parte della comunità, cosa molto importante. E abbiamo una considerazione notevole della riciclabilità di ogni sistema, elemento necessario e sufficiente per far partire una produzione. Cioè la riciclabilità diventa una questione fondamentale.

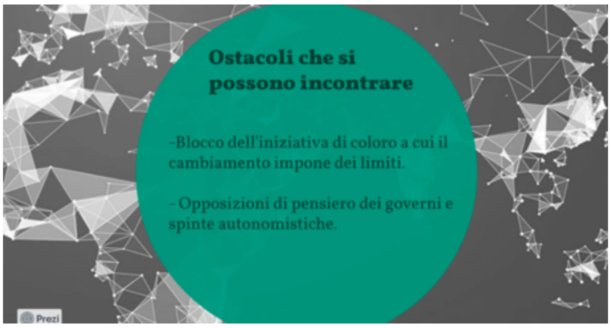
Di fianco ci sono tutti gli aspetti su cui si può lavorare e tutte le cose che invece potrebbero sbloccare la situazione. Esaminiamo per esempio l'Unione.

Noi abbiamo pensato che il modo più il modo più incisivo per riuscire ad avere una distribuzione abbastanza omogenea sarebbe creare un organismo sovranazionale. Nella fattispecie a rendere l'Onu esecutivo cioè che può dettare anche nei singoli stati legge. Questo faciliterebbe molto la cooperazione internazionale e riuscirebbe anche ad andare a tamponare dove ci sono le situazioni più disperate portando nelle situazioni più favorevoli risorse. Quindi se in tutto un pianeta abbiamo delle zone che magari la situazione non va molto bene, delle zone invece che va, quelle che si trovano meglio aiutano quelle che si trovano peggio [Dyn1].

L'interesse c'è l'interesse verso l'interesse generale c'è non rivolto a tante persone non a chi vive bene o a chi si trova in dei buoni paesi ma tutti. Quindi il più inclusivo possibile.

Le scelte legislative che abbiamo sarebbe l'abbattimento dei colossi che diciamo sguazzano in questo sistema andando a evadere cioè a scappare e a rifugiarsi nei cosiddetti paradisi fiscali per riuscire ad avere delle tassazioni minori quindi sfruttano questo sistema per il loro vantaggio. Ovviamente però creando alcune volte casi molto gravi di sfruttamento del lavoro oppure paga troppo bassa o inquinamento. Quindi abbattimento dei colossi che sfruttano questo sistema.

Riciclabilità come abbiamo detto. Come abbiamo visto quindi il riciclo deve essere inderogabile in ogni passaggio della produzione tutto deve essere fatto anche in funzione del riciclo.



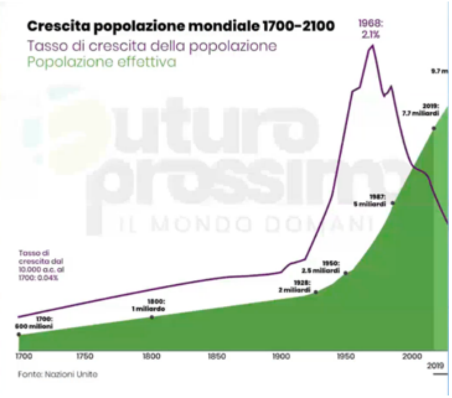
Poi abbiamo messo gli ostacoli. Cosa potrebbe negare questo questo futuro che abbiamo previsto il blocco dell'iniziativa di coloro il cui cambiamento impone dei limiti i famosi multinazionali coloro che hanno interessi molto grandi oppure no l'opposizione di pensiero di alcuni governi e spinte autonomiste di paesi, collettività o singole persone che controllano una collettività che non vuole fare parte di questo sistema [Dyn7].

In conclusione, lo scopo di questo non è tanto quello di rivoluzionare il sistema non è tanto quello di riportarlo e cambiarlo in ogni aspetto è solo una modifica. Quindi lo scopo è smussare il sistema per renderlo più inclusivo possibile, non rivoluzionario, senza fare battaglie ma solo cercando di non avere sprechi da una parte e povertà dall'altra ma cercare di rendere unita tutta la popolazione.

Group 2 – 7 billions (M6, M7, M8, M9, F10)

M8

34:01 Salve a tutti, noi abbiamo deciso di parlare di un problema di estrema attualità che è il sovrappopolamento e le conseguenze che potrebbe avere nel futuro [St4]. Qui abbiamo riportato un grafico che mostra l'andamento della popolazione e del tasso di crescita della popolazione dall'inizio diciottesimo secolo fino ai giorni nostri. Possiamo vedere in viola il tasso di crescita della popolazione che raggiunge il suo massimo all'incirca nell'anno 1968. E invece in verde la curva che rappresenta l'effettivo numero di abitanti della Terra. Possiamo vedere che dal ventesimo secolo ai giorni nostri la crescita è stata vertiginosa.



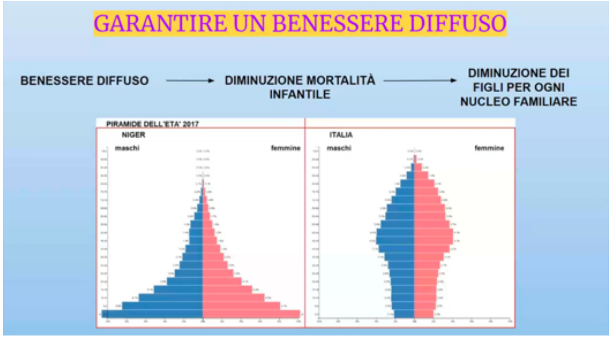
Quindi noi ci siamo chiesti quali potrebbero essere nel futuro i vari scenari [Dyn7].

Nel primo scenario abbiamo pensato che il consumo delle risorse possa diventare insostenibile. Abbiamo utilizzato come simulazione la wolf sheep predation con la variante dell'erba che si consuma, cioè le pecore devono mangiare erba per sopravvivere. Abbiamo aumentato l'intervallo di ricrescita dell'erba per simulare il lungo intervallo che serve alle risorse non rinnovabili come petrolio e combustibili fossili per essere di nuovo disponibili. Abbiamo aumentato anche la percentuale con cui le pecore si riproducono per accelerare il processo di crescita della popolazione. Possiamo vedere che la popolazione è cresciuta vertiginosamente ma ora possiamo vedere nel riquadro che le risorse, ad esempio il prato, è insufficiente a sostenere tutte… si è superata la portata del sistema e quindi la popolazione è destinata a subire un crollo [St3].

Il secondo scenario potrebbe essere diffusione di epidemie che sono legate all'aumento della densità abitativa e di conseguenza anche alle scarse norme igieniche che ci sono in alcuni agglomerati urbani, soprattutto nei paesi in via di sviluppo [St3]. Abbiamo introdotto qua i lupi che prima avevamo tolto perché non rappresentavano nulla… i lupi invece qua rappresentano gli agenti patogeni e per simulare l'alta densità abitativa è stato ridotto il riquadro da 25x25 a 15x15 quindi gli agenti erano più confinati e quindi i lupi dovevano percorrere minori distanze, quindi maggiore densità abitativa, per andare da una pecora all'altra. Quindi possiamo vedere che i lupi in brevissimo tempo si sono moltiplicati e le pecore sono diminuite. Il terzo scenario che noi preferiremmo sarebbe il raggiungimento di un apice stabile.

Ma come possiamo fare? Passo la parola a M6.

M6
37:07 Di sicuro uno dei fattori che in questo futuro ipotetico ha contribuito all'abbassamento della popolazione è stato sicuramente il garantire un benessere diffuso. Infatti anche al giorno d'oggi uno dei problemi principali è quello che, nei paesi in via di sviluppo, vi è un alto indice un alto tasso di natalità. Questo è dato dal fatto che le famiglie, i genitori per essere sicuri che alcuni dei loro figli arrivino nell'età adulta generano molti figli e questo va ad aumentare il tasso di natalità. Di conseguenza uno dei fattori, grazie a un benessere diffuso in tutto il mondo anche nei paesi in via di sviluppo è avvenuta questo futuro una diminuzione della mortalità infantile che ha portato come conseguenza alla diminuzione di figli per ogni nucleo familiare e quindi a una moderazione dell'accrescimento della popolazione.



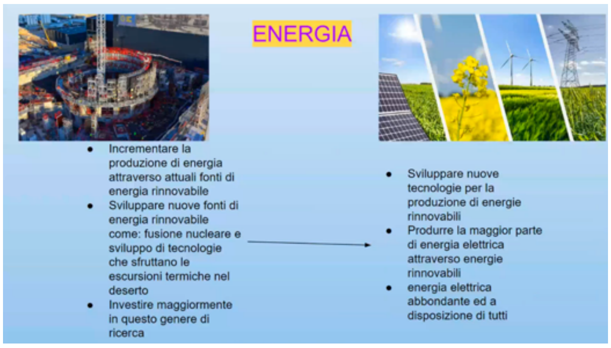
E però quali sono i fattori in questo futuro che hanno portato a un miglior stile di vita e a migliori possibilità?

Uno di questi è di sicuro la stipulazione degli accordi internazionali ovvero in questo futuro gli Stati hanno stipulato fra loro degli accordi che andassero a regolare lo sviluppo economico in modo che la ricchezza venisse diffusa in tutti i tipi e che quindi da questi accordi potessero trarne vantaggio principalmente quei paesi in via di sviluppo che di conseguenza hanno migliorato le loro condizioni di vita in questi Paesi e di conseguenza migliorato la qualità della vita ed è venuta a diminuire anche la mortalità infantile. Un esempio

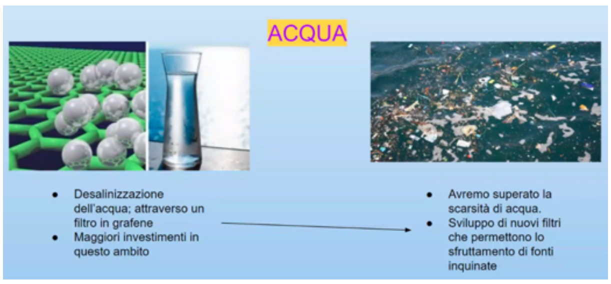
di accordo internazionale è quello dell'agenda 2030 che è stato stipulato nel 2015 e si è posto diversi obiettivi che gli Stati che hanno aderito a questo accordo si sono posti l'obiettivo di risolvere entro l'anno 2030. Tra questi problemi vi è ad esempio la lotta alla povertà estrema e alla fame ma anche alla diffusione della sanità e dell'istruzione in quei paesi che al giorno d'oggi non possono permetterseli o comunque sono poco diffusi.
Passo la parola al mio collega M7.

M7
40:07 Ecco un'altra delle questioni che permetterebbe il raggiungimento dell'obiettivo preposto sarebbe uno sfruttamento sostenibile della natura.

Quindi per via di un incremento della popolazione ci sarà bisogno di una maggior quantità di energia, di un miglior sfruttamento dell'acqua potabile dei territori.

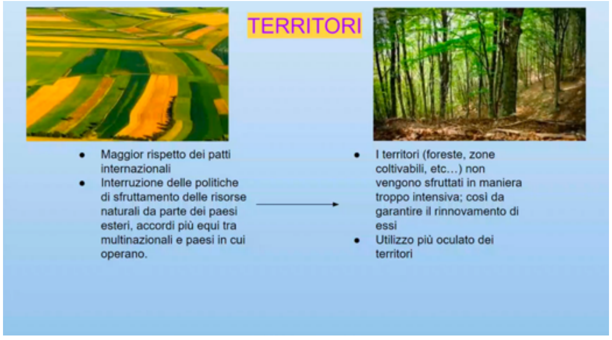


In particolare, nel caso dell'energia, sarà necessario sviluppare nuove tecnologie rinnovabili per produrre una maggior quantità di energia per sostenere una popolazione più grande e far sì che questa energia sia disponibile per tutti. Questo sarà possibile attraverso, insomma, sempre un miglioramento delle fonti di energia rinnovabile già preesistenti quindi pannelli solari o l'energia idroelettrica, lo sviluppo di nuove fonti di energia rinnovabili come potrebbe essere la fusione nucleare o lo sfruttamento di escursioni termiche nel deserto. Un esempio di fusione nucleare che è una tecnologia che è già stata testata e che stanno cercando di rendere utilizzabile è per esempio l'iter che stanno costruendo in Francia un grandissimo reattore a fusione nucleare. Ovviamente tutto questo dipende da maggiori investimenti in questo campo di ricerca.



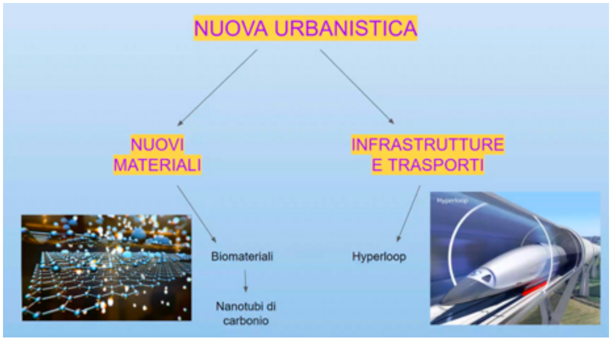
Altro tema molto importante è quello dell'acqua potabile perché con un aumento della popolazione ci sarà necessità di maggiore acqua potabile. Però attualmente si va incontro a una scarsità di acqua potabile. E infatti noi vorremmo che in questo futuro questa

scarsità di acqua potabile sia superata attraverso anche lo sviluppo di nuovi filtri che permettono anche di usufruire di fonti inquinate che permetterebbe un riciclo di ogni genere di acqua potabile. Poi attualmente in realtà è stato sviluppato abbastanza di recente un filtro in grafene capace di desalinizzare l'acqua e questo rende diciamo più economica la desalinizzazione dell'acqua. Ovviamente sempre ci sarà bisogno sempre comunque di un maggiore investimento di maggiori investimenti in questo ambito.
Per ultimo trattiamo i territori.



Ci sono moltissimi territori che andranno sfruttati in maniera sostenibile come per esempio foreste in zone coltivabili perché se vengono sfruttate in maniera troppo intensiva non ci sarà un rinnovamento di queste risorse. Ci sarà invece bisogno di rinnovamento di queste risorse e questo sarà dato da uno sfruttamento più oculato del territorio. Cos'è che permetterebbe questo rinnovamento dei territori che vengono sfruttati? Innanzitutto il rispetto dei patti internazionali che già esistono però non vengono rispettati molto spesso. E poi l'interruzione di politiche troppo invasive, troppo pesanti sulla natura come per esempio di paesi come il Brasile che stanno fruttando in maniera troppo estensiva le proprie risorse naturali come la foresta amazzonica e anche multinazionali che operano in questi paesi. Adesso passo la parola al mio collega.

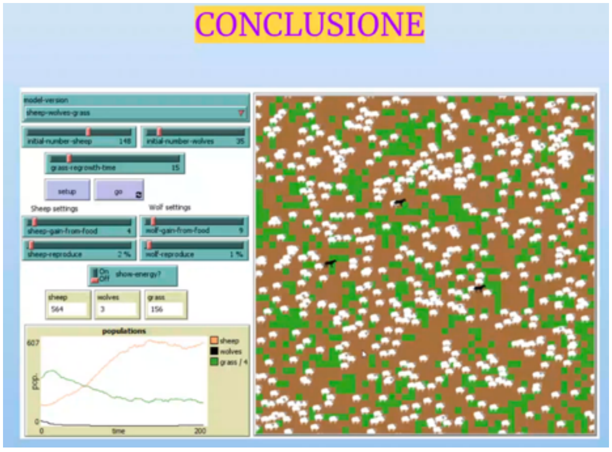
M9
45:05 Una delle sfide centrali in questo futuro sarà sicuramente la riprogettazione del dell'urbanistica.



45:16 Nel campo dei nuovi materiali vediamo i biomateriali e i materiali bio-ispirati che sfruttano delle caratteristiche naturali di organismi viventi. I nanotubi di carbonio sono un esempio di carbonio di calcio e invece nelle infrastrutture e trasporti. Un esempio è l'Hyperloop che consiste in capsule che viaggiano a 1.200 chilometri all'ora sospese grazie a magneti all'interno di un tubo di un tubo dove la densità dell'aria è molto minore rispetto a quella dell'atmosfera. E tra l'altro uno dei paesi sperimentali in cui la sperimentazione è più avanzata è proprio l'Italia.

M8

46:04 Per concludere servirebbe stabilire nuove norme igieniche riconosciute a livello mondiale che tutelino i mercati locali e i confini dei vari Stati dalla diffusione di epidemie, come si è visto per esempio in questi ultimi anni, o ad esempio di parassiti dell'agricoltura. In conclusione, sempre nella stessa simulazione siamo andati a lavorare sui vari parametri. È stato diminuito l'intervallo di ricrescita dell'erba legato a uno sviluppo sostenibile, è stata diminuita la percentuale con cui si riproducono le pecore per il benessere diffuso, sono stati depotenziati i parametri dei Lupi perché le nuove norme igieniche e la corretta urbanistica ha permesso uno sviluppo sostenibile che evitasse la diffusione di epidemie e si è potuto vedere che c'è una crescita vertiginosa confrontabile con quella degli ultimi 100 anni e poi si è stabilito su un apice che rimane invariato. Anche nella simulazione c'erano comunque delle oscillazioni ma erano molto meno marcate rispetto alle altre due simulazioni che abbiamo fatto vedere [Dyn2].



Group 3 – Doctor Strange (M12, M13, F14, F15)

F15

51:03 Allora noi abbiamo scelto come problema principale quello della globalizzazione, in particolare di quel fenomeno che sta portando tutte le popolazioni a un appiattimento della cultura [St2].

So, we chose globalization as the main problem to study. In particular, of the whole globalization we want to study that phenomenon which is leading all populations to a flattening of culture. **[St2]**

Quindi ci troviamo a non avere più quelle differenze culturali che in realtà sono importanti, secondo noi identificative per ogni singola popolazione. E quindi noi volevamo risolvere questo problema e quindi trovare un modo e quindi una via per evitare che succedesse ciò [St4]. E quindi siamo arrivati alla all'immaginazione di tre scenari completamente diversi [Dyn7].

So we notice that we no longer have those cultural differences that we think are actually important for each single population. And so, we wanted to solve this problem and then find a way to prevent this from happening. **[St4]** And so, we came up with the imagination of three completely different scenarios. **[Dyn7]**

51:48 Il primo scenario [Dyn7] è uno scenario [Dyn7] abbastanza estremista nel senso che la globalizzazione prende piede completamente. Quindi tutto il mondo, tutto il globo si trova sotto la stessa cultura [Dyn1] che può essere sia una cultura che si è creata dall'unione di tutte le culture che erano presenti oppure da una cultura diversa che ha come soppiantato tutte le altre e tutte le altre culture e quindi le popolazioni non sentono più la differenza tra di loro. Quindi le abitudini sono le stesse, i modi di vivere e anche di alimentarsi sono gli stessi e quindi non ci sono più quelle particolarità che prima erano casomai speciali nel caso uno andasse a viaggiare.
52:41 Il secondo [Dyn7] vede l'avvento della globalizzazione però questa globalizzazione non riesce a prendere piede in piccole zone di territorio [Dyn1] in cui queste popolazioni è come se si chiudessero come si isolassero e cercassero quindi di salvaguardare la loro cultura… e quindi sono cioè come gli

The first scenario **[Dyn7]** is quite an extremist scenario **[Dyn7]** in the sense that globalization takes hold completely. So, the whole world, the whole globe is under the same culture **[Dyn1]** which can be either a culture that was created from the union of all the cultures that were present, or from a different culture that has supplanted all the others. Therefore, the populations no longer feel the difference between them. So, the habits are the same, the ways of living and even eating are the same and therefore there are no longer those particularities that were previously special in case one travelled across countries.
The second scenario **[Dyn7]** sees the advent of globalization, but this globalization fails to take hold in small areas of the territory **[Dyn1]** where these populations are as if they are closing themselves off as they isolate themselves and therefore try to safeguard their culture ... and therefore they are like the Amish, that is, they isolate themselves from the rest of the world **[Dyn1]** to avoid losing their cultural identity.

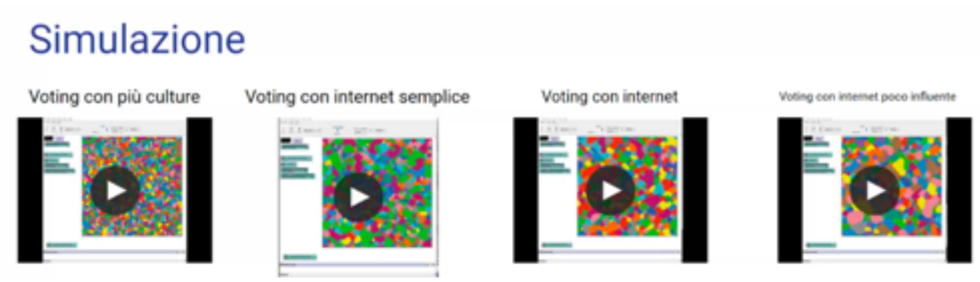
Amish, cioè si chiudono dal resto del mondo [Dyn1] per evitare di perdere quindi la loro identità culturale.
53:08 E poi invece il terzo scenario [Dyn7] che è quello dove la globalizzazione non riesce a prendere piede e quindi non si arriva a un appiattimento della cultura, anzi si arriva a una situazione di equilibrio in cui c'è una convivenza totale tra tutte le culture [Dyn1]. Quindi rimangono tutte le culture ma si trovano a convivere, quindi non ci sono più quegli scontri nel caso uno fosse diverso dall'altro e quindi ci si trova a una ottima e pacifica convivenza e nessuna cultura prevale sulle altre. Quindi non c'è una cultura che influenza le altre ma sono solo in contatto. Quindi uno può andarci in contatto, può conoscerle ma non si rischia di perdere la propria identità culturale andandoci in contatto.

And then instead the third scenario **[Dyn7]** which is the one where globalization fails to take hold and therefore a flattening of the culture is not achieved, indeed a situation of equilibrium is reached in which there is total coexistence between all cultures **[Dyn1]**. So, all cultures remain but they coexist, so there are no longer those clashes in case one is different from the other and therefore there is an excellent and peaceful coexistence, and no culture prevails over the others. So, there is no culture that influences the others, but they are just in contact. So, one can get in touch with them, can get to know them but there is no risk of losing their cultural identity by getting in touch with them.

M13

54:07 Abbiamo creato una simulazione basandoci partendo dal modello di voting ma estendendola [St1]. Quindi sono andato ad intervenire sul codice andando ad aggiungere la possibilità di avere più opinioni che qua. Cioè quelle che per il voting sarebbero opinioni… che qua vengono invece interpretate come culture differenti con una dinamica molto simile a quella del Voting, solo che appunto ogni casella ha la possibilità di avere attorno caselle di più di due colori differenti. E questo porta con sè la necessità di cambiare il modo in cui la simulazione funziona pesantemente.

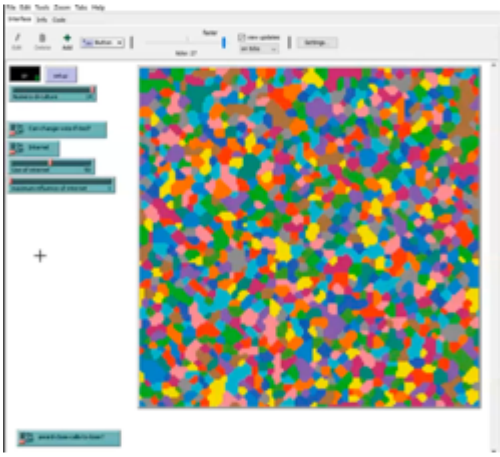
We created a simulation based on the voting model but extending it. So, I went to intervene on the code by adding the possibility of having more opinions than here. **[St1]** That is, those that for voting would be opinions… which here are instead interpreted as different cultures with a dynamic very similar to that of Voting, except that each patch has the possibility of having patches of more than two different colors around it. And that brings with it the need to change a lot the way the simulation works.



54:58 Infatti voting da solo, senza perderci troppo in ambito informatico… il modello del Voting lavora numericamente assegnando 1 o 0 e poi va a fare delle somme tra le caselle vicine ed è molto veloce, mentre non potendo più lavorare con 1 o 0 come il voting dato che abbiamo più valori che 1 o 0 di ogni colore, la simulazione si appesantisce e diventa molto lenta e per questo abbiamo dovuto lanciare simulazioni e poi prendere il video e velocizzarlo perché sennò sarebbe stato troppo. Una simulazione mi ha preso 12 minuti per finire per arrivare a termine quindi sarebbe stato come dire un po' proibitivo. Ecco inoltre ci sarebbe piaciuto anche includere nella simulazione le varie migrazioni, solo che non erano facilmente gestibili e quindi in un modello, nel momento in cui poi hai un dato che non riesce a gestire, è meglio non inserirlo perché sennò poi si va a creare solo confusione. [St1]
56:08 Poi per partire questo qua è un semplice voting [Dyn7]. Chiedo scusa per la qualità però me l'ha abbassate caricando. Questo è un semplice voting con più culture. Giusto per dare un

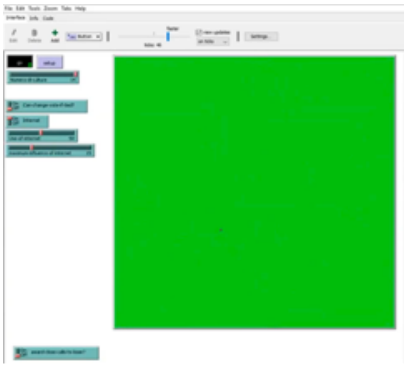
Without losing too much in the informatics aspects... the Voting model works numerically by assigning 1 or 0 and then goes to make sums between the neighboring boxes and is very fast. Now, not being able to work with 1 or 0 as in the Voting, given that we have more values, the simulation becomes heavier and slower. Here we would also have liked to include the various migrations in the simulation, but they were not easily manageable and, in a model, when you have a data that you cannot manage, it is better not to insert it because otherwise it will create just confusion. **[St1]**
Then to start this here is a simple voting **[Dyn7]**. I apologize for the quality but you have lowered it by loading. This is simple multi-culture voting. Just to give an example. This is the classic voting that we know it, we have seen it so we are not here to fossilize.

esempio. Questo è il voting classico che lo conosciamo, lo abbiamo visto quindi non stiamo qui a fossilizzarci.



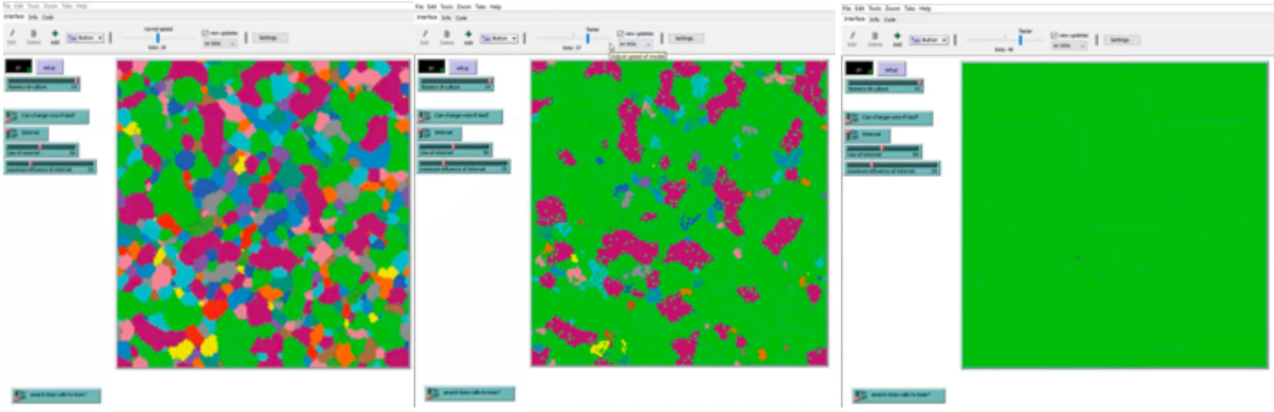
Qui invece abbiamo un voting che parte subito con Internet [Dyn 7].

Here, however, <u>we have a voting that starts immediately with the Internet</u>. **[Dyn7]**



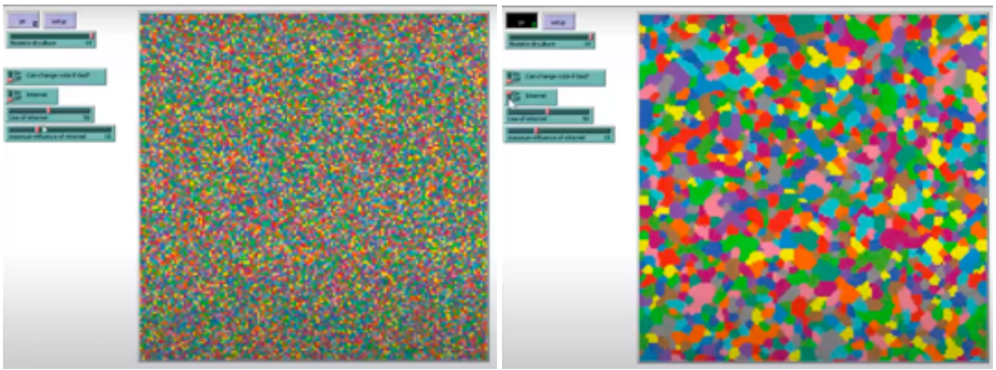
Abbiamo inserito questa meccanica di Internet per introdurre un po' questo tema della globalizzazione e internet cosa va a fare? Ci sono due parametri: c'è Internet che può essere acceso o spento e se viene acceso si attivano quei due parametri che si possono vedere di sotto. Uno è l'uso di Internet mentre l'altro è l'influenza massima che può avere internet su una persona. L'uso di Internet è la probabilità che una persona, quindi una casella vada su internet ogni giorno barra ogni anno, insomma ogni tic. Mentre l'influenza di Internet massima è un numero massimo di caselle casuali dal quale quella casella che quel giorno va su internet… dalle quali quella casella che va su Internet ha la possibilità di essere influenzata. Quindi questo è un voting semplice ovvero dove sin dall'inizio viene acceso Internet e quindi qua notiamo che c'è una prevalenza, c'è un appiattimento generale alla cultura.

We have inserted this mechanism of the Internet to introduce a bit this theme of globalization. What is the Internet doing? There are two parameters: there is the Internet that can be turned on or off and if it is turned on, those two parameters that can be seen below are activated. One is the use of the internet while the other is the maximum influence the internet can have on a person. The use of the Internet is the probability that a person, so an agent goes on the internet every day, every year, in short, every tick. While the maximum Internet influence is a maximum number of random agents from which that box that agent that access Internet has the possibility of being affected. So, this is a simple voting model where the Internet is turned on from the beginning and then we notice that there is a prevalence, a general flattening of the culture.



Mentre se adesso M12 mi passi a quella dopo… in questa invece abbiamo voluto raffigurare quella che è un po' più la situazione del nostro mondo ovvero un mondo che si è creato senza internet (e quindi all' inizio Internet era spento)… anche se adesso l'abbiamo già acceso. Se adesso mi torni un attimo all'inizio si può vedere che lascio clusterizzare. Si all'inizio che non si vede perché l'ho velocizzato.

Whereas if M12 now passes me to the next one... in this instead we wanted to depict what is a little more the situation of our world **[Dyn7]**, that is a world that was created without the internet (and therefore at the beginning the Internet was off)... even if now we have already turned it on. If you go back to the beginning for a moment, you can see that I let it cluster. Yes, at the beginning you don't see it because I speeded it up.

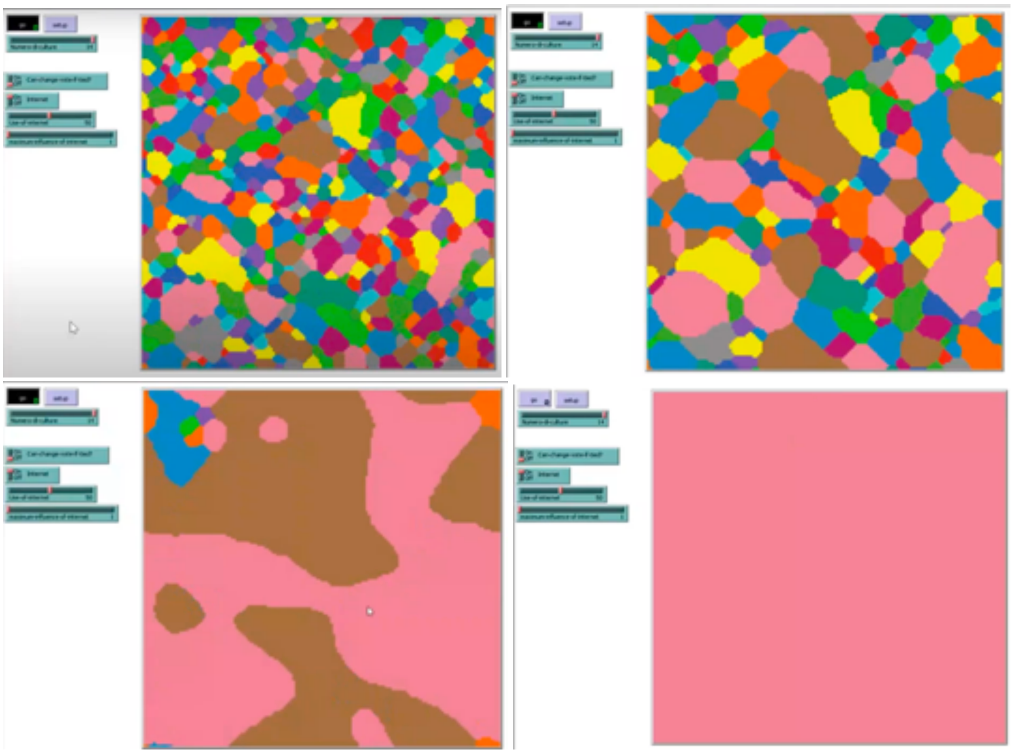


Scusate però vi assicuro che all'inizio avevo lasciato clusterizzare le culture e poi avevo acceso Internet successivamente, un po' simulando quello che è stato alla realtà… ovvero l'umanità senza internet poi è stata messa in contatto. E anche qui notiamo che nonostante la classificazione preliminare c'è un appiattimento generale della cultura.

Then I let cultures cluster and turned on the Internet, somewhat simulating what was the reality... that is, humanity without the Internet was then put in contact. And here too we note that despite the preliminary classification there is a general flattening of the culture.

Abbiamo fatto varie prove [Dyn7] e abbiamo visto che sempre ogni volta che accendevamo Internet le culture tendevano ad appiattirsi.
E anche qui dove ho sempre lasciato clusterizzare prima e poi ho acceso Internet [Dyn7] ma con un internet che sia il 50 per cento di probabilità ma che ogni casella va al massimo a prendere da una sola casella, si può notare come seppur più lente… infatti se guardate il numero dei tick in alto prima ci fermavamo a poche centinaia qua arriviamo a circa 2000… e poi rimane un quadratino Marrone perché è bello citarlo se tagliate la fine del video però anche quella si può intuire che poi sarebbe sparita. Ecco qua siamo arriviamo a 3mila tic. Per quanto molto più lento come processo porta a un appiattimento generale della cultura.

We did various tests ***[Dyn7]*** *and saw that every time we turned on the Internet, cultures tended to flatten out.*
And also here where I have always let it cluster first and then I turned on the Internet ***[Dyn7]*** *but with an internet that is 50% likely but that each box fetches from a single box at the most, it can be seen that although slower ... in fact if you look at the number of ticks at the top before we stopped a few hundred here we get to about 2000 ... and then there remains a Brown square because it is nice to mention it if you cut the end of the video but you can also guess that then it would have disappeared. Here we are we reach 3 thousand tics. Although much slower as a process it leads to a general flattening of the culture.*



Questo probabilmente è un problema del nostro modello oppure è una conseguenza che noi non vediamo perché troppo lontani negli anni… [Dyn7] su questo non sta a me deciderlo. Però a livello matematico si può capire che ciò accade perché statisticamente nei momenti in cui una cultura prevale su un'altra aumenta la probabilità che ogni casella vada ad essere influenzata da quella cultura e di conseguenza avviene quello che avviene, ovvero un appiattimento delle culture [St3, Dyn7].

This is probably a problem with our model, or a consequence that we do not see now because we are too far in the years… ***[Dyn7]*** *on this it is not up to me to decide. But at a mathematical level it can be understood that this happens because statistically in the moments in which one culture prevails over another the probability that each patch will be influenced by that culture increases and consequently what happens is that we can observe an overall flattening of the cultures.* ***[St3, Dyn3]***

F14

01:00:17 Dunque, il nostro scenario desiderabile per il 2040 è sicuramente quello in cui le varie culture si influenzano tra loro senza che però nessuna di esse prevalga sulle altre e quindi avvenga un appiattimento culturale a causa della globalizzazione [Dyn1]. È quindi un futuro in cui i confini politici e territoriali non costituiscono più un limite per lo scambio di idee e il confronto.

E però è comunque un futuro in cui rimaniamo molto legati alle nostre origini e in questo futuro ogni ambiente pubblico diventa un'occasione di confronto e di scambio con persone di etnie anche molto diverse dalle nostre [Dyn3]. E abbiamo anche pensato che una persona si allontani e cerca di nascondere la propria cultura quando non si sente totalmente accettata. E quindi il nostro futuro vuole essere libero dai pregiudizi e dagli stereotipi e dev'essere caratterizzato dall'accoglienza per cui se una persona si sente apprezzata e fa della sua cultura e delle sue tradizioni un punto di forza e non qualcosa da nascondere [Dyn3]… quindi il nostro scenario è caratterizzato da una mentalità aperta [Dyn3] in cui sicuramente possiamo prendere il meglio da ciascuna cultura con cui veniamo in contatto grazie anche alle nuove tecnologie rimanendo però sempre molto legati alla nostra identità culturale che ci rende unici e diversi dagli altri [Dyn3]. Passo la parola a M12.

Therefore, our desirable scenario for 2040 is certainly one in which the various cultures influence each other without, however, none of them prevailing over the others and without a cultural flattening occurring due to globalization. ***[Dyn1]*** *Hence, it is a future in which political and territorial borders no longer constitute a limit for the exchange of ideas and comparison.*

And yet it is still a future in which we remain very attached to our origins and in this future every public event becomes an opportunity for comparison and exchange with people of very different ethnic groups from ours. ***[Dyn3]*** *And we also thought that a person walks away and tries to hide their culture when they don't feel totally accepted. Our future wants to be free from prejudices and stereotypes and must be characterized by welcoming people.* ***[Dyn3]*** *Hence our scenario is characterized by open mindset* ***[Dyn3]*** *in which we can certainly take the best of each culture with which we come in contact thanks also to new technologies while always remaining very attached to our cultural identity that makes us unique and different from others.* ***[Dyn3]*** *I pass the floor to M12.*

M12

01:02:21 La strada verso il 2040 desiderabile ovviamente non sarà semplice perché ci saranno diverse rivolte contro le decisioni più rivoluzionarie e decisioni che più nuove più che nessuno si aspettava [Dyn5]. Ad esempio, l'eliminazione dei confini geografici e politici o l'eliminazione del passaporto o l'apertura verso l'immigrazione ad esempio. Queste diverse ci saranno diverse idee nella società e questo potrebbe portare alla creazione di fazioni o comunque punti di scontro per diverse idee contrapposte tra di loro. [Dyn5] Durante questo

The road to a desirable 2040 will obviously not be easy because there will be several revolts against the most revolutionary and newest decisions than no one expected. ***[Dyn5]*** *For example, the elimination of geographical and political borders or the elimination of the passport or the opening towards immigration for example. These different there will be different ideas in society and this could lead to the creation of factions or in any case points of conflict for different ideas opposed to each other.* ***[Dyn5]*** *There will be two main bifurcation points* ***[Dyn5]*** *in this* processo per arrivare al futuro desiderabile ci saranno due punti principali di biforcazione. [Dyn5] Il primo tra gli scenari che noi abbiamo chiamato 1 e 3, ovvero tra la globalizzazione massima cioè con una cultura che prende il sopravvento sulle altre, e lo scenario 3 che è quello desiderabile in cui tutte le culture non si influenzano tra di loro senza che nessuno prevalga. Il secondo punto di biforcazione sarà invece tra gli scenari 2 e 3 ovvero tra la globalizzazione che potremmo chiamare media cioè con una cultura che è più diffusa delle altre ma con minoranze ancora presenti, e lo scenario 3 che è lo scenario del futuro desiderabile. Per arrivare al 2040 che noi desideriamo ci si dovrà fare affidamento all'incontro tra le diverse culture che caratterizzano il mondo di oggi che si potrebbero influenzare tra di loro attraverso i social media o anche attraverso i viaggi quando potremo riprendere a farli. La convivenza quindi tra queste culture potrà essere di due tipi: o coesistenza e quindi valorizzazione di ognuna, oppure sostituzione da parte di una cultura predominante e quindi cancellazione dell'individualità. Ma starà a ognuno di noi decidere quale futuro vogliamo [Dyn3].

process of arriving at the desirable future. The first of the scenarios that we have called 1, that is between maximum globalization, that is with one culture that prevails over the others, and scenario 3 which is the desirable one in which all cultures do not influence each other without no one prevails. The second bifurcation point will instead be between scenarios 2 and 3 or between globalization that we could call media, that is with a culture that is more widespread than the others but with minorities still present, and scenario 3 which is the scenario of the desirable future. To get to the 2040 that we want, we will have to rely on the encounter between the different cultures that characterize the world today that could influence each other through social media or even through travel when we will be able to do it again. The coexistence between these cultures can therefore be of two types: either a real co-living and mutual enhancement of each one, or replacement by a predominant culture and cancellation of individuality. ***[Dyn3]*** *But it will be up to each of us to decide what future we want.*

Group 4 – Change the School (M16, F17, M18, M19, M20)

M20

01:10:58 Allora come metodo di presentazione abbiamo scelto di creare una pagina Instagram nella quale abbiamo inserito cinque post riguardanti il nostro tema [St4].

01:11:09 Ora se volete mando anche link della pagina così potete accedervi tutti.

*So as a method of presentation we have chosen to create an Instagram page in which we have inserted <u>five posts regarding our theme</u>. **[St4]***

Now if you want I can also send links to the page so that you can all access it.

[Testo del post: *Ormai la nostra società appare rivoluzionata dall'introduzione di sempre più nuove tecnologie, ci troviamo nell'era digitale, fase storica caratterizzata dall'ampia diffusione di vari prodotti digitali che hanno cambiato in maniera significativa il nostro approccio alla cultura, al modo in cui passiamo il tempo libero, al mondo del lavoro.*

Come ragazzi ci sentiamo molto presi in causa quando si parla di nuove tecnologie perché siamo "nativi digitali". Si sa, il computer è divenuto indispensabile alla vita dell'uomo e la scuola non può non essere immune da questo ingente cambiamento.

L'introduzione dei dispositivi digitali a scuola è una tematica notevolmente dibattuta e che ancora oggi divide e crea polemiche, la tecnologia dal canto suo può offrire comunque uno stimolo per migliorare il metodo d'insegnamento classico (nozionistico e frontale) rendendolo sociale e interattivo.

Le risorse digitali di cui facciamo uso possono essere condivise con tutti, in qualsiasi momento e in qualsiasi luogo. Come studenti troviamo molto utile avere l'opportunità di rivedere o riascoltare una lezione, cosi come poter approfondire argomenti grazie ai materiali condivisi dai docenti e facilmente reperibili in Rete, in tal modo è possibile rielaborare ogni cosa in tempi più rilassati; è evidente che la scuola ci stia offrendo un'opportunità di apprendimento aumentata. Con tutta evidenza la tecnologia propone un valido supporto nello studio grazie all'integrazione dei tipici linguaggi del digitale: testi, immagini, video e audio. Insieme al gruppo ci siamo focalizzati anche sulla questione voti, una pratica insistente e diffusa che mette molto spesso in difficoltà noi ragazzi; quello che vorremmo non è un'abolizione totale perché si sa, essi sono fondamentali anche per una valutazione di noi stessi, ma una trasformazione in voti espressi in lettere (come ad esempio negli Stati Uniti) in tal modo in ragazzi si sentirebbero meno stressati di fronte a una verifica o interrogazione.

[Caption of the post: By now our society appears to have been revolutionized by the introduction of more and more new technologies, we are in the digital age, a historical phase characterized by the widespread diffusion of various digital products that have significantly changed our approach to culture, the way we spend our free time in the world of work.

As kids we feel very concerned when it comes to new technologies because we are "digital natives". You know, the computer has become indispensable to human life and the school cannot fail to be immune from this huge change.

The introduction of digital devices at school is a highly debated issue that still divides and creates controversy today. Technology for its part can still offer a stimulus to improve the classical teaching method (notional and frontal) by making it social and interactive.

The digital assets we use can be shared with anyone, anytime, anywhere. As students we find it very useful to have the opportunity to review or listen to a lesson again, as well as being able to deepen topics thanks to the materials shared by the teachers and easily available on the Net, in this way it is possible to rework everything in more relaxed times; it is clear that the school is offering us an increased learning opportunity. The technology clearly offers valuable support in the study thanks to the integration of the typical digital languages: texts, images, video and audio. Together with the group we also focused on the question of votes, an insistent and widespread practice that very often puts us kids in difficulty; what we would like is not a total abolition because you know, they are also fundamental for an evaluation of ourselves, but a transformation into votes expressed in letters (such as in the United States) in this way children would feel less stressed than in the face of a verification or questioning.

Siamo certi che sia un cambiamento complesso ma è un buon modo per avvicinarsi sempre di più al mondo di oggi, decisamente digitalizzato, nel quale i veri protagonisti siamo noi giovani.]

We are sure that it is a complex change but it is a good way to get closer and closer to today's world, definitely digitalized, in which the real protagonists are us young people.]

01:11:29 Allora i problemi su cui ci siamo focalizzati sono inerenti alla scuola e sono due. Il primo, quello principale, riguardante il metodo di insegnamento. Il secondo è il tipo di voti [St2]. Noi riteniamo che il metodo di insegnamento classico nozionistico e frontale sia noioso e poco interattivo e per renderlo per migliorarlo diciamo bisognerebbe far maggior uso di dispositivi digitali in classe. È un tema abbastanza attuale perché con la questione Covid siamo stati per molti mesi a casa. E la tecnologia è risultata abbastanza utile, anzi molto. La tecnologia è sicuramente un buon strumento di insegnamento e di apprendimento, se affiancato chiaramente al cartaceo e quindi ai libri.
Un altro punto su cui ci siamo focalizzati è la questione dei voti scolastici i quali abbiamo notato che diciamo mettono un po' di difficoltà nei ragazzi. Non parliamo quindi di una abolizione totale ma di un passaggio da voti espressi in numeri a voti espressi in lettere dell'alfabeto, come ad esempio avviene in America [Dyn5]. Questa è un po' la descrizione del post riguardante il problema. Ora lascio la parola a Francesca che parlerà delle simulazioni che abbiamo utilizzato.

So, the problems we focused on are inherent to school and are two. The first, the main one, concerns the teaching method. The second is the type of grades. **[St2]** We believe that the classical notional and frontal teaching method is boring and not very interactive and to improve it we should use more digital devices in the classroom. It is a fairly recent issue because we have been at home for many months with the Covid. And the technology turned out to be quite useful, indeed a lot. Technology is certainly a good teaching and learning tool, if clearly combined with paper and therefore with books.
Another point on which we have focused is the question of school grades which we have noticed that let's say they put a little difficulty in the students. So, we are not talking about a total abolition but a passage from votes expressed in numbers to votes expressed in letters of the alphabet, as is the case in America, for example. This is a bit of the description of the post regarding the problem. Now I leave the floor to my colleague who will talk about the simulations we used.

F17

[Testo del post:

Simulazione: Cooperation simulation

Agenti:
Mucca egoista: coloro che sostengono il vecchio stile di insegnamento e di apprendimento.
Mucca cooperativa: coloro che sostengono il nuovo stile di insegnamento e di apprendimento.
Erba: appoggio degli studenti.

Meccanismo:
Entrambe si nutrono dell'appoggio degli studenti, ma, mentre le mucche collaborative (coloro che promuovono le nuove modalità) portano avanti le proprie iniziative affiancandole alla volontà degli studenti e regolandosi di conseguenza, in modo tale che il loro consenso possa sempre rimanere abbastanza alto per finanziare ulteriori innovazioni (giunti al consenso del

[Caption of the post:

Simulation: Cooperation simulation

Agents:
Selfish cow: those who support the old style of teaching and learning.
Cooperative cow: those who support the new style of teaching and learning.
Erba: student support.

Mechanism:
Both nourish themselves on the support of the students, but, while the collaborative cows (those who promote the new modalities) carry out their own initiatives alongside them to the will of the students and adjust themselves accordingly, so that their consent can always remain high enough to finance further innovations (reached the consensus of 70% of the students, they

70% degli studenti, smettono di persuadere coloro non ancora convinti, in modo tale che possa ricrescere il consenso per nuovi cambiamenti e non fermare il processo di innovamento), le mucche golose si impongono sugli studenti in maniera più rigorosa (cercano di convincere quasi tutti gli studenti a mantenere i metodi tradizionali), perdendo sempre di più l'appoggio degli studenti, che tenderà a riformarsi sempre più lentamente [St3].

Varianti:
Initial-cows: numero di mucche golose è maggiore di quello delle mucche collaborative
Metabolism (Metabolismo): ad ogni azione i sostenitori sia dei vecchi sia dei nuovi modelli di apprendimento perdono parte del guadagno che hanno ottenuto con l'appoggio degli studenti.
Reproduction-cost (Costo di riproduzione): costo economico necessario per portare aventi le proprie iniziative (ad esempio l'acquisto di nuovi dispositivi elettronici, l'assunzione di nuovi professori, l'aumento dei viaggi di istruzione e delle attività extra scolastiche).
Reproduction-threshold (Limite di energia per la riproduzione): finanziamento necessario per portare aventi nuove iniziative, nuovi miglioramenti.
Grass-energy (Energia che fornisce l'erba): finanziamenti da parte degli studenti.
Max-grass-height (Altezza massima dell'erba): appoggio quasi totale da parte degli studenti (gli studenti pongono quasi completamente la fiducia nelle nuove modalità di istruzione).
Low-high-threshold (Limite di crescita dell'erba): appoggio minimo da parte degli studenti (gli studenti non sono molto d'accordo con le nuove modalità di istruzione, ma comunque continuano in parte a sostenerle, sperando in un miglioramento futuro).

Scenari possibili:
- *raggiungimento di un equilibrio tra vecchi e nuovi metodi di insegnamento e apprendimento (nessuno dei due dovrebbe prevalere sull'altro, poiché entrambi presentano modalità utili e fondamentali [St4] per raggiungere il più adatto metodo di istruzione) —> scenario desiderabile*
- *eccesso utilizzo dei nuovi metodi di istruzioni, che può comportare ad esempio un esagerato uso delle nuove tecnologie e di conseguenza un aumento dei rischi legati ad esse (nella simulazione: scomparsa dei vecchi metodi, che si impegnano a tenere sotto controllo l'educazione scolastica, impedendo che avvenga un suo cambiamento totale e irreversibile, anche se imponendosi sugli studenti).*
- *incapacità dei modi innovativi di insegnamento di imporsi nelle scuole (nella simulazione: scomparsa dei nuovi metodi e presenza soltanto di quelli vecchi, che tendono a soccombere le necessità e le volontà delle nuove generazioni, senza evolversi insieme alle nuove tecnologie).]*

01:13:26 Fra le varie simulazioni che pensavamo potessero riprodurre bene presto questa nostra tematica, abbiamo scelto

stop persuading those not yet convinced, so that they can regrow the consensus for new changes and not stop the process of innovation), greedy cows impose themselves on the students in a more rigorous way (they try to convince almost all the students to keep the traditional methods), losing more and more the support of the students, who will tend to reform more and more slowly [St3].

Variants:
Initial-cows: number of greedy cows is greater than that of collaborative cows
Metabolism: with each action the supporters of both the old and the new learning models lose part of the gain they have obtained with the support of the students.
Reproduction-cost (cost of reproduction): economic cost necessary to carry out one's own initiatives (for example, the purchase of new electronic devices, the hiring of new professors, the increase in educational trips and extra-curricular activities).
Reproduction-threshold (Energy limit for reproduction): funding needed to bring new initiatives, new improvements.
Grass-energy (Energy that provides grass): student funding.
Max-grass-height: almost total support from students (students almost completely place their trust in the new ways of education).
Low-high-threshold (Weed Growth Limit): minimal support from students (students disagree very much with the new ways of education, but still continue to support them in part, hoping for future improvement).

Possible scenarios:
- *achieving a balance between old and new teaching and learning methods (neither should prevail over the other, since both have useful and fundamental ways [St4] to achieve the most suitable teaching method) -> desirable scenario*
- *excessive use of new methods of instruction, which can lead, for example, to an exaggerated use of new technologies and consequently an increase in the risks associated with them (in the simulation: disappearance of old methods, which undertake to keep school education under control , preventing its total and irreversible change from taking place, even if it imposes itself on the students).*
- *inability of innovative ways of teaching to establish themselves in schools (in the simulation: disappearance of new methods and presence only of old ones, which tend to succumb to the needs and wills of the new generations, without evolving together with new technologies).]*

<u>*Among the various simulations that we thought could reproduce this issue of ours, we chose cooperation because in our opinion it was more suited to this topic*</u>. ***[St1]*** *So as agents*

la cooperation. perché secondo noi si adattava di più a questo argomento [St1]. Allora come agenti abbiamo scelto le mucche golose Come diciamo coloro che sostengono i vecchi tradizionali metodi di insegnamento, come invece le mucche cooperative tutti coloro che invece sostengono comunque voglio portare avanti nuovi metodi di insegnamento e di apprendimento come invece l'erba appunto abbiamo pensato che potesse essere proprio l'appoggio, il sostegno da parte degli studenti. Allora il meccanismo l'abbiamo già visto nelle lezioni precedenti. Comunque l'abbiamo spiegato in questo modo, ovvero che quindi entrambe, sia quelle più golose sia quelle cooperative, si nutrono dell'appoggio degli studenti [St3]. Tuttavia, mentre le mucche collaborative tendono a portare avanti le proprie iniziative affiancando la volontà degli studenti e adeguandosi di conseguenza, ad esempio non vogliono imporsi sugli studenti ma preferiscono che quindi avere l'appoggio necessario per avere i finanziamenti derivanti appunto proprio dall'appoggio degli studenti per portare avanti i propri cambiamenti [St3]. Ma non vogliono imporsi ma lasciare magari una parte degli studenti, come se ci fosse diciamo l'appoggio – non so chi abbia già studiato Aristotele - in potenza che diventa in atto con il finanziamento, in modo tale che questo processo di confronto e di cambiamento possa andare continuamente avanti facendo in modo che la scuola possa essere sempre all'avanguardia per nuove tecnologie, eccetera. Ecco invece quindi le altre mucche si impongono sugli studenti in questo modo, cercano di ottenere tutto l'appoggio degli studenti e quindi abbassano anche un futuro appoggio nuove e magari iniziative e impediscono quindi agli studenti di confrontarsi, di ottenere magari una scuola che possa adeguarsi di più alle loro nuove esigenze [St3]. Poi abbiamo diciamo attribuito alcuni significati alle varianti… va beh ad esempio il costo di riproduzione come costo necessario per portare avanti nuove iniziative. Poi abbiamo scelto come abbiamo già stabilito che sicuramente il numero delle mucche golose sarà maggiore di quello delle mucche cooperative. Poi, non so ad esempio che appunto l'energia dell'erba fosse quindi il finanziamento da parte degli studenti. Il metabolismo che ad ogni azione le mucche sia quelle golose sia quelle collaborative perdevano parti dell'energia e quindi diciamo dei propri soldi magari tenuti da parte.

*we have chosen the greedy cows as, we say, those who support the old traditional teaching methods. Instead, the cooperative cows [are] all those who want to carry on new teaching and learning methods. The grass we thought that could be the support from the students. So, we have already seen the mechanism in previous lessons. <u>However, we have explained it in this way, that is, therefore both, both the greedy ones and the cooperative ones, are nourished by the support of the students</u>. **[St3]** However, collaborative cows tend to carry out their own initiatives by supporting the will of the students and adapting accordingly. For example, <u>they do not want to impose themselves on the students but prefer to have the necessary support to have the funding deriving from the support of the students to carry out their own changes</u>. **[St3]** [...] It is as if there was, let's say, the support - I don't know who has already studied Aristotle - in potentiality that becomes active with the financing, so that this process of comparison and change can go on continuously by doing so that the school can always be at the forefront of new technologies. Instead, <u>the other cows impose themselves on the students, they try to get all the support of the students, they prevent the students from confronting each other, perhaps obtaining a school that can better adapt to their new needs</u> **[St3]**. Then we attributed some meanings to the variants… for example, we saw the cost of reproduction as the cost necessary to carry out new initiatives. Then we have already established that surely the number of greedy cows will be greater than that of cooperative cows. Then for example we decided that weed energy was student funding. The metabolism corresponds to the fact that with every action the cows, both the greedy ones and the collaborative ones, lose energy which is, let's say, the money they had saved.*

Da questa simulazione abbiamo trovato che i possibili scenari che andiamo poi a approfondire meglio anche più in pratica potrebbero essere [Dyn7]: quello più desiderabile è l'equilibrio fra le vecchie tradizioni e invece quelli vecchi metodi di insegnamento quelli invece più innovativi perché pensiamo che tutti e due possano essere utili e fondamentali in realtà per raggiungere una tipologia di scuola, di moderno insegnamento più adatto agli studenti [Dyn5]. Gli altri due sono più diciamo gli estremi ovvero che prevalgano solamente i nuovi metodi di insegnamento e che quindi possano diciamo così abbandonare alcune magari modalità che invece sono utili per l'insegnamento e magari aumentare i rischi dovuti alle nuove tecnologie [St4]. E invece d'altra parte abbiamo quindi la mancanza imposizione: i nuovi metodi non riescono a imporsi

*<u>From this simulation we have found possible scenarios</u>. **[Dyn7]** The most desirable is the <u>balance between the old traditions, the old teaching methods, and the more innovative ones, because we think that both can be useful and fundamental to reach a type of school, of modern teaching more suitable for students</u>. **[Dyn5]** The other two are more, let's say, the extremes, that is, only the new teaching methods prevail; therefore, some modalities that are useful for teaching are abandoned <u>and perhaps the risks due to new technologies increase</u>. **[St4]** And instead on the other hand we have the lack of imposition: the new methods fail to impose themselves in schools and we do not get a change.*

And then we started from the fact that a possible solution of the simulation that can then be applied in reality is that the cost of reproduction could be lowered. For example, in practice this can nelle scuole e quindi non si ottiene quest'altro ma questo cambiamento.

E poi siamo partiti dal fatto che una possibile soluzione della simulazione che può essere quindi applicata nella realtà è che si potrebbe abbassare il costo di riproduzione. Ad esempio, nella pratica ciò può equivalere ad esempio a fare in modo che il governo possa sostenere i costi necessari per nuovi cambiamenti e quindi fare in modo che i nuovi metodi all'interno delle scuole possano realizzarsi in maniera più semplice e più rapida. Passo la parola al mio collega che invece ci dirà i possibili futuri [Dyn7].

amount, for example, to ensuring that the government can bear the costs necessary for new changes and thus making it easier and faster to implement new methods within schools.

*I pass the floor to my colleague who is going to tell us the possible futures **[Dyn 7]***

M18

[Testo del post:

1) Incremento dell'uso della tecnologia che sta diventando sempre più presente nell'educazione, e ci aspettiamo che continuerà ad accrescere la sua presenza. [Dyn2]

2) Diversa gestione dei tempi utilizzando anche i pomeriggi per fare rientri e corsi

3) Introduzione di attività nuove ovvero i corsi pomeridiani di cui abbiamo parlato pocanzi.

4) Rivalutazione dell'attività sportiva a fronte di tempo maggiore da destinare alle lezioni cosa che renderà più importante muoversi.

5) Nuovi metodi di insegnamento che si adattino ai tempi che evolvono ed usano i nuovi strumenti.

6) Rapporti umani favoriti anche dai rientri a scuola.

Con il passare degli anni le nostre vite sono cambiate radicalmente con l'avvento di nuovi strumenti tecnologici, quindi pensiamo sia molto probabile che questi nuovi mezzi diventino strumenti indispensabili per la scuola del futuro. Anche grazie alla pandemia la tecnologia è divenuta sempre più presente all'interno dei metodi di insegnamento e ci aspettiamo che si continuerà così anche dopo essere usciti da questo triste momento. Abbiamo però anche considerato come probabilmente ci sarà anche un'opposizione da parte di chi invece sostiene che passare troppe ore davanti allo schermo fin da piccolissimi potrebbe nuocere alla salute, inoltre dare strumenti complessi a bambini che non sono in grado di comprenderne i rischi potrebbe essere controproducente, quindi, alla luce di queste osservazioni, abbiamo pensato che probabilmente queste tecnologie verranno utilizzate a partire dalle scuole medie.

[Cpotion of the post:

1) Increase in the use of technology which is becoming more and more present in education, and we expect it will continue to increase its presence. [Dyn2]

2) Different management of times, also using the afternoons to make returns and courses

3) Introduction of new activities or the afternoon courses we have just talked about.

4) Re-evaluation of sporting activity in the face of more time to be allocated to lessons, which will make it more important to move.

5) New teaching methods that adapt to evolving times and use new tools.

6) Human relationships also favored by the return to school.

Over the years, our lives have changed radically with the advent of new technological tools, so we think it is very likely that these new tools will become indispensable tools for the school of the future. Also thanks to the pandemic, technology has become increasingly present within teaching methods and we expect that this will continue even after we have come out of this sad moment. However, we also considered how likely there will also be opposition from those who argue that spending too many hours in front of the screen from an early age could harm health, moreover giving complex tools to children who are not able to understand the risks could be counterproductive, therefore, in the light of these observations, we thought that probably these technologies will be used starting from middle school.

Furthermore, we have in fact realized that, especially in this period of virtual teaching, there are many practical aspects related to the advent of new technologies that are often

Inoltre ci siamo infatti accorti che, specialmente in questo periodo di didattica virtuale, ci sono molti aspetti pratici legati all'avvento delle nuove tecnologie che spesso nelle scuole vengono trascurati, ad esempio il semplice scrivere una mail può risultare a volte complicato visto che sono pochi i professori che si sono realmente soffermati su questo argomento spiegandoci le modalità per essere più efficaci durante la stesura. Quindi, avendo notato come molti professori si sono accorti della problematica, molto probabilmente potrebbero implementare all'interno del loro programma anche queste attività cosa che gli porterebbe anche ad approcciarsi a nuovi metodi di insegnamento. Ci aspettiamo quindi che, oltre alle sempre più diffuse lavagne elettroniche, si inizieranno ad usare anche computer e tablet, quest'ultimi potrebbero poi interagire fra loro grazie alla diffusione di un una nuova piattaforma che permette una maggiore sinergia all'interno del gruppo classe permettendo anche al docente di esaminare in un qualsiasi momento il lavoro che lo studente sta svolgendo. Per quanto riguarda questi strumenti probabilmente saranno gli stessi genitori degli studenti che dovranno procurarsi tali dispositivi ma noi confidiamo nel fatto che lo stato rilasci dei fondi per le famiglie in difficoltà economiche.

Analizzando il funzionamento di scuole estere abbiamo anche pensato che sarebbe meglio, e a parer nostro anche probabile che si realizzi, che nel futuro ci sarà una migliore gestione dei tempi magari utilizzando anche il pomeriggio per avere anche la possibilità di fare studio di gruppo. Infatti, troppe ore molto dense non portano ad ottenere i risultati che si vorrebbe, di conseguenza si potrebbe organizzare la scuola in modo che le ore diventino magari più lunghe ma meno intense e che siano intervallate da più pause, anche se questo potrebbe richiedere anche l'uso di alcuni pomeriggi. Così facendo diventa più facile anche seguire ed organizzare corsi extra che potrebbero avvicinare sempre più studenti a mondi sconosciuti facendogli comprendere meglio anche quale possa essere la loro strada, magari potrebbero anche essere utili per fine di aiutare lo studente nella scelta dell'università. Dobbiamo anche precisare come probabilmente a molti potrà sembrare assurdo rimanere il pomeriggio ma va sottolineato come se si impara di più e meglio a scuola, il lavoro di ogni studente a casa diminuisce sensibilmente, lasciando alla fine molto più tempo libero di prima.

Trascorrendo così tanto tempo a scuola si sentirà poi il bisogno di fare anche attività fisica e quindi magari potrebbero essere utile implementate alcune discipline sportive come materie o come attività facoltative all'interno della scuola. Un po' come si rivede negli USA con le squadre di basket. Questo, insieme ai corsi, potrebbe avere anche un forte impatto per quanto riguarda i rapporti umani, soprattutto fra alunni e docenti che dovranno avvicinarsi sempre di più. Questo potrebbe anche portare molti studenti ad avvicinarsi di più alle materie studiate sentendo magari i professori più vicini.

neglected in schools, for example simply writing an email can sometimes be complicated since there are few. the professors who have really focused on this topic, explaining how to be more effective during the drafting. Therefore, having noticed how many professors have noticed the problem, most likely they could also implement these activities within their program, which would also lead them to approach new teaching methods. We therefore expect that, in addition to the increasingly widespread electronic whiteboards, computers and tablets will also start to be used, the latter could then interact with each other thanks to the spread of a new platform that allows greater synergy within the class group allowing also the teacher to examine at any time the work that the student is doing. As for these tools, it will probably be the parents of the students who will have to procure these devices but we are confident that the state will release funds for families in financial difficulty.

Analyzing the functioning of foreign schools we also thought that it would be better, and in our opinion also likely that it will happen, that in the future there will be a better management of times, perhaps even using the afternoon to also have the opportunity to study in a group. In fact, too many very dense hours do not lead to obtaining the results that you would like, consequently you could organize the school so that the hours may become longer but less intense and that they are interspersed with more breaks, even if this could also require the use of some afternoons. By doing so, it also becomes easier to follow and organize extra courses that could bring more and more students closer to unknown worlds, making them better understand their path, perhaps they could also be useful in order to help the student in choosing a university. We must also clarify how probably it may seem absurd to many to stay in the afternoon but it should be emphasized that if you learn more and better at school, the work of each student at home decreases significantly, leaving in the end much more free time than before.

Spending so much time at school will then feel the need to do physical activity and therefore maybe some sports disciplines could be useful as subjects or as optional activities within the school. A bit like what we see in the USA with basketball teams. This, together with the courses, could also have a strong impact on human relationships, especially between pupils and teachers who will have to get closer and closer. This could also lead many students to get closer to the subjects studied, perhaps hearing the closest professors.

To conclude, except for the courses and technology, we can say that we have tried not to imagine changes that would require huge expenses precisely because it would be difficult for the government to allocate the necessary amount for the construction of major works [Dyn5]. We also were maybe a bit too optimistic to say that this will be the reality that will be breathed in twenty years, but we believe that this is a path that

Per concludere, tranne per quanto riguarda i corsi e la tecnologia, possiamo dire che abbiamo cercato di non immaginare cambiamenti che necessitassero di ingenti spese proprio perché sarebbe difficile che il governo riesca a stanziare la somma necessaria per la realizzazione di grandi opere [Dyn5]. Inoltre siamo stati forse un po' troppo ottimisti dicendo che questa sarà la realtà che si respirerà fra vent'anni ma riteniamo che questa sia una strada alla quale prima o poi ci avvicineremo nonostante magari i cambiamenti si vedranno dopo molti più anni [Dyn7].

Inoltre abbiamo osservato anche un aumento del numero delle esperienze scolastiche, sia per quanto riguarda gli stage nelle aziende e sia per il numero delle gite che vengono fatte. Tutto ciò sta diventando sempre più evidente anche grazie all'introduzione di un monte ore destinato all'alternanza scuola lavoro che tende ad aumentare ed un numero di uscite scolastiche che pensiamo saranno più frequenti.]

sooner or later we will approach despite the changes that may be seen after many more years [Dyn7].

We have also observed an increase in the number of school experiences, both in terms of internships in companies and in the number of trips that are made. All this is becoming increasingly evident also thanks to the introduction of a number of hours intended for school-work alternation which tends to increase and a number of school exits that we think will be more frequent.]

01:18:30 Abbiamo analizzato che nel corso di questa pandemia l'utilizzo delle tecnologie sta diventando sempre più ricorrente. In particolare, abbiamo anche considerato come probabilmente queste nuove tecnologie tenderanno a diventare quasi quotidianità forse anche a partire dalle scuole medie [Dyn2]. Infatti noi abbiamo considerato l'utilizzo di strumenti tecnologici a partire da scuole più elementari proprio perché molto probabilmente passare tante ore davanti agli schermi fin da piccoli può portare anche a vizi della postura o a danneggiare anche la salute e quindi molto probabilmente ci saranno delle forti opposizioni che andranno a limitare anche l'uso della tecnologia per quanto riguarda appunto i primi anni della scuola e quindi probabilmente si arriverà a un livello nel quale si utilizzeranno con una buona sequenza anche dispositivi elettronici quali computer e tablet durante le lezioni a partire dalle scuole medie, a nostro parere. In particolare stavamo anche immaginando una possibile piattaforma che permetta una migliore sinergia in modo che appunto l'insegnante possa anche entrare all'interno del lavoro di ogni studente per vedere in tempo reale quello che sta svolgendo permettendo anche di comprendere meglio le motivazioni per le quali magari si è bloccato in un problema e poi non riesce ad andare avanti.
01:20:04 Inoltre abbiamo anche immaginato che nuovi metodi di insegnamento si adattino a una nuova gestione dei tempi che per noi deve essere un pochino migliorata. Infatti, le lezioni ci appaiono forse troppo dense e quindi molto spesso diventa anche difficoltoso riuscire a cogliere al meglio tutte le nozioni che ci vengono fornite. Quindi abbiamo anche immaginato delle lezioni magari più lunghe che però contengono la stessa quantità di informazioni in modo che queste ultime siano diluite nel tempo. Ovviamente ci siamo resi conto che oltre a esserci la possibile soluzione di accorciare il piano formativo magari andando a togliere alcuni elementi più nazionalistici che verranno poi dimenticati, potrebbe essere comodo appunto anche utilizzare il pomeriggio in modo che si possano organizzare anche delle ore nelle quali gli studenti possono

*We have discussed that <u>during this pandemic the use of technologies is becoming more and more recurrent. In particular, we have also considered how probably these new technologies will tend to become almost everyday life, perhaps even starting from middle school</u>. **[Dyn2]** In fact, we have considered the use of technological tools starting from the lower levels of education because spending many hours in front of screens from an early age can also lead to posture defects or even damage health. So, probably there will be strong opposition which will also limit the use of technology during the first years of school. In our opinion we will probably reach a level in which electronic devices such as computers and tablets will also be used with a good sequence during lessons starting from middle school. We were also imagining a possible platform that allows a better synergy so that the teacher can also enter the work of each student to see in real time what they are doing, also allowing to better understand the reasons for which maybe they are stuck in a problem and can't move forward.*
Furthermore, we also imagined that the new teaching methods adapt to a new time management that for us needs to be improved a little. In fact, the lessons are too dense and very often it is difficult to grasp all the notions. We also imagined longer lessons that contain the same amount of information so that the latter are diluted over time. Obviously, we realized that in addition to being the possible solution to shorten the training plan perhaps by removing some more nationalistic elements that will then be forgotten, it could also be convenient to use the afternoon so that we can also organize hours in which the students can also come together to study in groups, perhaps even with some professors. We have also noticed that in this way the time available could also grow exponentially because a quality study would be made that would allow us to reduce the time for self-study. But this will then be better narrated by my mate.
We also noticed how having the afternoons available to students would be even more incentivized to take courses that

riunirsi per fare anche studio di gruppo magari anche con qualche professore. Abbiamo anche notato che così il tempo a disposizione potrebbe anche crescere esponenzialmente perché si farebbe uno studio di qualità che permetterebbe appunto di ridurre il tempo da dedicare allo studio autonomo. Ma questo verrà poi narrato meglio dal nostro compagno. Subito dopo abbiamo notato anche come avendo a disposizione dei pomeriggi gli studenti sembra anche più incentivati a fare dei corsi che potrebbero per portarli anche ad avvicinare a esperienze che non appunto mai fatto nella loro vita e potrebbero così facendo anche avere un'idea migliore di quale possa essere la loro attitudine. Potrebbe anche essere utile per farli orientare a un percorso universitario. Inoltre passando così tanto tempo a scuola diventa anche necessario svolgere attività fisica. Di conseguenza abbiamo immaginato anche un futuro nel quale le scuole organizzino dei momenti sportivi anche all'interno delle lezioni come succede per esempio in America con il basket… sappiamo appunto che le squadre sono proprie della scuola e quindi potrebbe essere anche utile per favorire la parte riguardante l'aspetto motorio.
01:22:40 Inoltre con l'incremento dei rientri a scuola sarebbero favoriti i rapporti umani sia tra gli studenti che tra professori e studenti facendo sì che appunto si vada anche a rivalutare quella che è la nostra immagine del docente che sennò viene visto come un personaggio austero che vuole metterci esclusivamente in difficoltà quando in realtà quest'ultimo è comunque una persona che magari condivide nostri stessi interessi e si potrebbe creare anche un legame migliore. Inoltre abbiamo anche immaginato che nel futuro potrebbero diventare sempre più presenti le gite scolastiche o comunque gli stage per acquisire anche nuove conoscenze molto più variegate rispetto a quelle che si possono apprendere a scuola. Inoltre abbiamo prestato particolare attenzione a non immaginare un futuro che richiedesse grandi fondi da parte dello Stato perché ci siamo resi conto che sarebbe molto più lungo il tempo per poterle implementare tutte quante all'interno del nostro futuro e di conseguenza, a parte quanto, riguarda le nuove tecnologie, abbiamo immaginato un futuro che fosse realizzabile anche senza grandi fondi [Dyn5].

could lead them to approach experiences that they have never done in their life and in doing so they could also have a better idea of which may be their attitude. It could also be useful for orienting them to a university course. In addition, since the students will spend so much time at school, would become necessary physical activity. Consequently, we have also imagined a future in which schools organize sporting moments even within the lessons as happens for example in America with basketball...
Furthermore, with the increase of afternoons spent at school, human relationships would be favored both among students and between professors and students, making sure that we also go to re-evaluate what is our image of the teacher who otherwise is seen as an austere character who wants to put ourselves in difficulty when in reality is in any case a person who perhaps shares our same interests and a better bond could also be created. Furthermore, we also imagined that in the future school trips or internships could become more and more present to acquire new knowledge much more varied than those that can be learned at school. <u>We also paid particular attention not to imagine a future that would require large funds from the state because we realized that it would take much longer to implement them all within our future and consequently, apart from what concerns new technologies, we imagined a future that was achievable even without large funds</u>. ***[Dyn5]***

M16

[Testo del post: *Dopo aver pensato a quali potrebbero essere i possibili futuri, ci siamo soffermati su quale potrebbe essere, idealmente, il migliore tra essi. Abbiamo poi cercato di*

[Caption of the post: After thinking about what the possible futures might be, we focused on which could be, ideally, the best of them. We then tried to describe it on what could be the perfect typical day.

descriverlo in quella che potrebbe essere la giornata-tipo perfetta.
Ore 9-13: Lezioni mattutine. Orario d'inizio un po' posticipato per essere più svegli e presenti già alla prima lezione. Ogni mattina si svolgono 4 ore di lezione da 50 minuti con una pausa da 10 alla fine di ciascuna.
Ore 13-14.30: Pranzo e relax. A seconda dell'attività del pomeriggio ogni classe e studente si organizza per il pranzo e si prende un po' di tempo per il riposo.
Ore 14.30-17: Attività pomeridiane, che possono includere lezioni online, attività di studio collettivo, allenamenti, corsi extra scolastici, attività di laboratorio, incontri con esperti. Ogni studente, a seconda delle necessità, può tuttavia organizzare se ha problemi di orari il proprio programma: atleti, ballerini, attori e ogni altro tipo di impegno che occupa del tempo in più ha diritto ad un'organizzazione particolare.
Dalle ore 17 la giornata scolastica ufficiale è terminata. Se però si ha bisogno di fare studio aggiuntivo o altre attività chiaramente c'è il tempo. Eventualmente per aggiungere anche lavori per cittadinanza e costituzione, da quest'ora delle classi ad orari alterni si possono occupare a ordinare e pulire gli ambienti scolastici, per avere una scuola più pulita.
Dal tardo pomeriggio alla sera non ci dovrebbe essere necessità di studio, in quanto durante la giornata molto tempo è stato dedicato a ciò. Si può uscire con gli amici, stare con la famiglia o riposarsi.]

9-13: Morning lessons. Starting time a bit postponed to be more awake and present at the first lesson. Each morning there are 4 hours of lessons of 50 minutes with a break of 10 at the end of each.
13-14.30: Lunch and relaxation. Depending on the activity in the afternoon, each class and student arranges for lunch and takes some time to rest.
2.30-5pm: Afternoon activities, which may include online lessons, collective study activities, training, extra-curricular courses, laboratory activities, meetings with experts. Each student, according to need, can however organize their own program if they have time problems: athletes, dancers, actors and any other type of commitment that takes up extra time is entitled to a particular organization.
From 5 pm the official school day ended. However, if you need to do additional study or other activities, there is clearly time. Possibly to also add jobs for citizenship and constitution, from this hour on, classes at alternate hours can be occupied in ordering and cleaning the school environments, to have a cleaner school.
From late afternoon to evening there should be no need for study, as much time has been devoted to this during the day. You can go out with friends, stay with family or rest.]

01:24:07 Sì allora io diciamo abbiamo provato a immaginare quale potrebbe essere un giorno per noi studenti nel nostro futuro migliore, nel caso in cui tutte i nostri progetti siano andati nel migliore dei modi. Quindi abbiamo pensato che la mattina potrebbero esserci delle lezioni come adesso però dalle 9 alle 13 quindi fare 4 ore… quindi iniziare un po' dopo rispetto adesso… va beh lasciamo stare la situazione del virus che nel nostro futuro ideale la nostra giornata ideale dovrebbe già essere finita la pandemia quindi insomma immaginiamo una giornata normale senza virus. Quindi quattro ore di lezioni per tutti che finiscono alle 13 orario nel quale comincia con una pausa pranzo che può essere usata per mangiare ma anche per riposarsi.
E poi nel pomeriggio abbiamo pensato che i rientri a scuola possano essere effettivamente molto utili. Chiaramente le lezioni la mattina sono lezioni meno nozionistiche ma lezioni in cui vengono insegnate le cose ma si parla molto anche dell'applicazione poi materiale perché poi nel pomeriggio all'orario che va dalle 14 30 alle 17 circa… poi è chiaro che abbiamo dato un po' un'immagine ma oggettivamente poi si può cambiare si può un attimo pensare come farla meglio… però durante queste ore può essere possono essere svolte attività di laboratorio o incontri con esperti con visite come gite o visite per esempio dei musei e appunto per esempio il discorso sportivo che oggi oggettivamente è quasi un intralcio la vita sportiva fuori da scuola per uno studente… quindi diciamo che sono tutte attività che il pomeriggio è importante fare secondo me oltre per esempio a uno studio pomeridiano

We tried to imagine what a day could be for us, as students, in our best future, in case all our projects have gone in the best way. So, we thought that in the morning there could be lessons like now but from 9 a.m. to 1 p.m. so 4 hours... so start a little later than now... okay, let's forget the virus situation because in our ideal future the pandemic should be over… so let's imagine a normal day without virus. So 4 hours of lessons for all that end at 1 p.m.. Then we have a lunch break to eat and rest. And then in the afternoon we thought that going back to school could actually be very useful. Clearly the lessons in the morning are lessons in which things are taught but there is also a lot of talk about the applications. Because in the afternoon from 2 to 5 p.m.… then it is clear that we have given a bit of an image but of course you can think about how to do it better... but during these hours, laboratory activities or meetings with experts can be carried out, or trips or visits to museums, sports… these are all activities that in the afternoon it is important to do as well as for example study in pairs or even with professors. In this way the human relationship is valued, and we move away from a concept of frontal teaching but a teaching that aims more at education and less at leading you to know notions that are often forgotten. Then from 5 p.m., let's say, the personal activities can begin. So, if one needs further study, they can study again or rest or carry out fun and relaxation activities. This is an aspect that we think it is neglected today, time for oneself today is a bit neglected because in any case we are always busy with tests during the year. Maybe even the management of the school timetable as it is distributed throughout the year... maybe avoid leaving three summer months but dividing it better could be collettivo tra studenti alla pari o anche con professori. In questo modo il rapporto umano viene valorizzato e ci si allontana più da una concezione di insegnamento frontale ma un insegnamento che mira più all'istruzione in sè e meno a oggettivamente sapete le cose che poi vengono anche spesso dimenticate molte nozioni. Poi appunto dalle 17 possono iniziare diciamo le attività più personali. Quindi se uno ha bisogno di ulteriore studio può studiare ancora oppure può già cominciare a riposarsi oppure svolgere le sue attività di divertimento e di relax. Questo è un aspetto che pensiamo che oggi ci sia poco, il tempo per sé stessi oggi è un po' trascurato perché comunque siamo sempre presi da interrogazioni e verifiche almeno durante l'anno. Anche la gestione magari dell'orario scolastico come viene distribuito durante l'anno… magari evitare di lasciar tre mesi estivi ma suddividerlo meglio potrebbe risultare molto funzionale. E poi la sera è tempo da dedicare agli amici o alla famiglia che è sempre più importante nella vita. Questa è un po' la nostra giornata ideale. Per le conclusioni passo la parola al mio collega.

very functional. And then the evening is time to dedicate to friends or family which is increasingly important in life. This is a bit like our ideal day. For the conclusions I leave the floor to my colleague.

M19

01:27:28 Allora io parlerò soprattutto dei problemi principali e di cosa possiamo fare.

Then I will mainly talk about the main obstacles and what we can do.

[Testo del post:
Sostegno del governo e del ministero: gli studenti e i docenti che vogliono una cambiamento nel sistema scolastico italiano devono farsi sentire attraverso petizioni e movimenti su social media e mass media [Dyn3].
-"Il programma scolastico non deve essere ridotto": a questa obiezione di potrebbe rispondere attraverso degli esempi pratici, infatti si potrebbero istituire delle scuole "innovative" che abbiano il programma scolastico modificato, con un'organizzazione basata sul modello ideale già citato e un tipo di insegnamento all'avanguardia, così che si possano avere dei dati concreti per provare che la scuola attuale non è per forza la migliore e che deve cambiare.
-trovare insegnanti disposti a provare nuovi metodi di insegnamento: si potrebbero organizzare dei corsi di aggiornamento per insegnanti che vogliono sperimentare nuove forme di insegnamento, che diano spazio anche alle proposte dei docenti stessi in modo tale da avere varie opinioni e, attraverso una comunicazione più efficace con gli studenti, anche un'approvazione da parte dei diretti interessati.

[Caption of the post:
Government and ministry support: students and teachers who want a change in the Italian school system must make themselves heard through petitions and movements on social media and mass media [Dyn3].
- "The school program must not be reduced": this objection could be answered through practical examples, in fact "innovative" schools could be established that have a modified school program, with an organization based on the ideal model already mentioned and a state-of-the-art type of teaching, so that we can have concrete data to prove that the current school is not necessarily the best and that it must change.
- find teachers willing to try new teaching methods: refresher courses could be organized for teachers who want to experiment with new forms of teaching, which also give space to the proposals of the teachers themselves in such a way as to have various opinions and, through a more effective with students, including approval by those directly involved.
-fostering peer teaching: already now there are projects for students who are willing to help others, but they are not sufficiently exploited and often those who join aim only at

-favorire l'insegnamento fra pari: già adesso sono presenti dei progetti per studenti che sono disposti ad aiutarne altri, però non somo sufficientemente sfruttati e spesso chi aderisce punta solo a remunerazioni personali come il credito scolastico. Tuttavia, sono occasioni sprecate in quanto un confronto fra studenti può essere talvolta molto più efficace di uno fra insegnante e studente, in quanto gli adolescenti fra di loro riescono a comprendersi molto meglio, aiutando anche a risolvere dei dubbi che non vengono chiariti dalla spiegazione del docente.

-necessario sforzo da parte di tutti, soprattutto gli studenti: come si sarà potuto notare il contributo degli studenti è essenziale affinché questi mutamenti possano accadere. Quindi è di vitale importanza fare capire quanto sia decisivo il loro contributo per attuare un cambiamento così radicale ed è fondamentale farli risvegliare dalla passività nei confronti della scuola che alberga molto spesso fra i giovani, spesso a causa di un forte antagonismo verso le istituzioni scolastiche che vengono quasi viste come torture [Dyn3].]

01:28:01 Innanzitutto è necessario un sostegno da parte del governo, del Ministero proprio per aumentare i fondi per la scuola, per istituire delle scuole o dei progetti che le singole scuole non possono fare. [Dyn4]

01:28:34 Per questo è necessario in una sorta di attivismo da parte degli studenti e dei docenti che quindi possono fare petizioni oppure anche di movimenti sul social media ai mass media [Dyn4]. In questo modo, molta più gente verrebbe in contatto con questo pensiero [Dyn3, Dyn4] e magari si diffonderebbe anche il modo più veloce dato che possiamo sfruttare uno strumento che tuttora è al giorno d'oggi molto prevalente nella vita soprattutto dei giovani. Poi ci sarebbe l'obiezione che il programma scolastico non dev'essere ridotto. Per far fronte a questo problema si potrebbero istituire delle scuole innovative sparse un po' in tutta Italia in modo da ottenere dei dati che possano essere paragonati effettivamente a quelli che ci sono adesso con la scuola tradizionale [Dyn4]. In questo modo si potrebbe ribattere al fatto che il programma scolastico è già ideale come è adesso, quando invece può essere cambiato e deve essere cambiato. Inoltre, è difficile anche trovare degli insegnanti disposti a provare nuovi metodi di insegnamento. In questo caso si potrebbero istituire dei progetti o dei corsi per i docenti stessi in modo tale che abbiano occasione di confrontarsi fra di loro per ideare dei nuovi metodi di insegnamento e magari anche discuterne con gli studenti in modo da averne l'approvazione [Dyn4]. Un altro punto importante è l'insegnamento fra pari, qualcosa che adesso è già presente però non viene sfruttato abbastanza. Infatti la maggior parte degli studenti che aderiscono a questi progetti lo fanno per remunerazioni personali, quindi come crediti scolastici, e non pensano effettivamente a quanto siano efficaci queste occasioni. Per questo sarebbe utile pubblicizzare questi eventi e renderli comuni in tutte le scuole.

Infine è necessario uno sforzo da parte di tutti, soprattutto degli studenti. Infatti sono gli studenti stessi a mobilitarsi in prima

personal remuneration such as school credit. However, they are wasted opportunities as a confrontation between students can sometimes be much more effective than one between teacher and student, as adolescents are able to understand each other much better, also helping to resolve doubts that are not clarified by the explanation of the professor.

-necessary effort on the part of everyone, especially the students: as you may have noticed, the contribution of the students is essential for these changes to happen. Therefore it is of vital importance to understand how decisive their contribution is to implement such a radical change and it is essential to awaken them from the passivity towards the school that is very often found among young people, often due to a strong antagonism towards the educational institutions that they are almost seen as torture [Dyn3].]

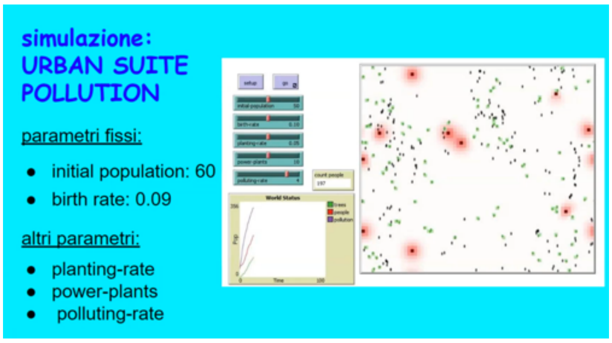
*First of all, support is needed from the government, from the Ministry to increase funds for the school, to set up schools or projects that individual schools cannot do **[Dyn4]**. For this it is necessary in a sort of activism from students and teachers who can start petitions or even movements on social media or mass media **[Dyn4]**. In this way, many more people would encounter these ideas and maybe it would also spread faster since we can exploit a tool [the social media] that is still very prevalent today in the life especially of young people. Then there would be the objection that the school curriculum should not be cut. To cope with this problem, innovative schools could be set up in Italy to obtain data that can actually be compared to those that exist now with traditional schools **[Dyn4]**. In this way one could see if the school program is already ideal as it is now, or if it can be changed and what needs to be changed. Furthermore, it is also difficult to find teachers willing to try new teaching methods. In this case, projects or courses could be set up for the teachers themselves so that they can confront each other to devise new teaching methods and perhaps even discuss them with the students to have their approval **[Dyn4]**. Another important point is peer instruction, something that is already present now but is not being exploited enough. For this it would be useful to publicize these events and make them common in all schools. Finally, an effort is needed on the part of everyone, especially the students. In fact, it is the students themselves who mobilize themselves to bring about a change in Italian education **[Dyn4]**. For this it is necessary to awaken in a certain sense the students from the passivity that harbors these days. More than passivity I would say indifference towards the school, since now it is almost like torture many times. For this we need movements that can reach everyone, so that they realize that the school can change, and they can do something to help **[Dyn3]**.*

persona per portare un cambiamento nell'istruzione italiana [Dyn4]. Per questo è necessario risvegliare in un certo senso gli studenti dalla passività che alberga in questi giorni, in questo periodo. Più che passività direi indifferenza nei confronti della scuola, dato che ormai viene molte volte quasi come una tortura. Per questo sono necessari dei movimenti che riescano a raggiungere tutti, in modo tale che si rendano conto che la scuola può cambiare e loro possono fare qualcosa per aiutare [Dyn3].

Group 5 – Bubble (F21, M22, M23, M24, M25)

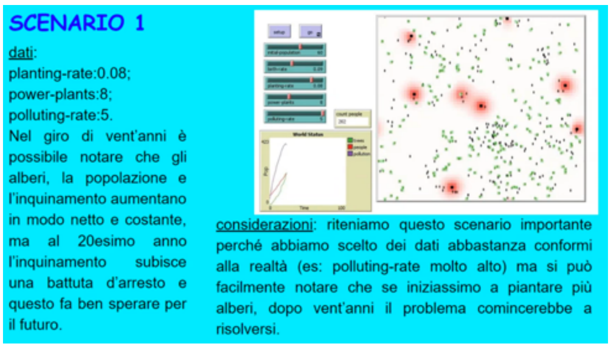
M25
01:41:36 Noi parleremo dell'inquinamento dell'aria nella pianura padana.

01:41:58 Abbiamo scelto questo tema perché comunque anche questo è un tema di attualità che ci tocca tutti e che se appunto non viene risolto andremo a finire in una situazione abbastanza spiacevole.



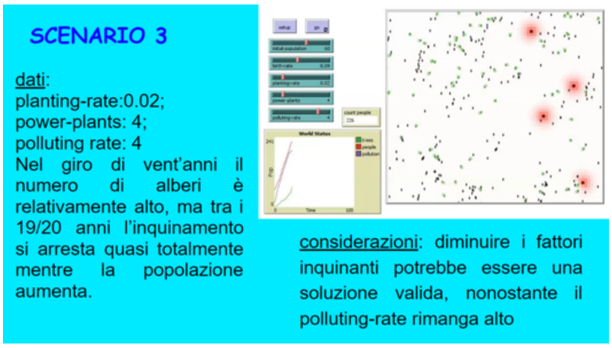
Come simulazione abbiamo utilizzato quella della urban suite pollution. Adesso vi spiego un po' come ce l'abbiamo gestita. Allora abbiamo ottenuto dei parametri fissi che sono initial population e birth rate. Li abbiamo diciamo scelti così perché ci siamo basati su dati reali e abbiamo appunto quindi voluto fare una simulazione più realistica possibile per avere come risultato una cosa abbastanza realistica. Abbiamo quindi tenuto quei due parametri fissi. Initial population è la popolazione iniziale mentre il tasso delle nascite in ogni anno. Gli altri parametri invece sono il planting rate, quanti alberi vengono piantati in un anno. Il power plant invece sono quei fattori inquinanti, se così posso descriverli che sono. Se vedete nell'immagine sono quelle zone rosse. Mentre il polluting rate è invece quanto inquinamento viene creato da questi power plant. Questi invece li abbiamo variati per avere un po' di situazioni diverse [Dyn7] per avere anche le tre simulazioni da confrontare tra di loro. Ve le spiegherà Martina.

F21
01:43:48 Allora



01:43:51 il primo scenario era appunto come ha già detto Besam… abbiamo tenuto come dati fissi initial population e planting rate. Poi abbiamo scelto come dati appunto planting rate 0.08, power plants 8 e polluting rate 5. Abbiamo fatto la simulazione prendendo come tempo 20 anni fino al 2040 e come si può vedere da questo grafico, che allora l'inquinamento che appunto è questo viola aumenta appunto in modo netto, costante e raggiunge valori anche abbastanza alti. Anche se poi comunque sembra fermarsi e sembra appunto diminuire gradualmente. E allora a questo punto eravamo un po' curiosi di sapere come sarebbe andata avanti la simulazione e vedendo poi come sarebbe proseguita abbiamo poi effettivamente notato che l'inquinamento negli anni successivi sarebbe sceso di gran lunga. Quindi anche questo insomma ci ha fatto capire che avevamo scelto insomma dei dati buoni. E quindi già nel giro di 20 anni comunque attraverso questi dati abbiamo visto delle buone speranze per il futuro. E quindi riteniamo proprio questo scenario importante perché comunque i dati che abbiamo scelto non si discostano più di tanto dalla realtà. Per esempio, abbiamo tenuto un polluting rate molto alto e un power plants abbastanza altino. E quindi. E però appunto se piantiamo molti alberi mettendo un planting rate alto, già nel giro di 20 anni si possono notare dei netti miglioramenti. Il problema comunque si risolverebbe
01:46:06

lo scenario 2 invece è molto diverso perchè abbiamo scelto un planting rate molto basso,
01:46:15 un power plant abbastanza alto e un polluting rate sempre a alto e quindi abbiamo visto che con dei dati così la situazione peggiora drasticamente. In realtà anche in questo caso abbiamo analizzato la situazione, la simulazione anche dopo 20 anni. abbiamo visto che la tendenza nel grafico nel giro di 20 anni appunto prosegue cioè appunto l'inquinamento raggiunge livelli molto alti mentre la popolazione cresce in modo costante ma abbastanza lentamente. Invece il numero di alberi piantati è veramente basso. Quindi ciò che abbiamo pensato comunque è se effettivamente non si fa nulla per migliorare la situazione, quindi se non si piantano più alberi, se quindi non si adottano delle decisioni migliori [Dyn2, St3].
01:47:24 Abbiamo chiamato questo scenario uno scenario drastico perchè comunque la situazione peggiorava decisamente.
01:47:35



L'ultimo scenario invece è un po' più positivo. Nonostante appunto abbiamo un planting rate comunque molto basso, un power plants 4 e un polluting rate sempre alto… comunque l'inquinamento comunque sale tantissimo. Però a differenza dello scenario prima anche la popolazione aumenta anche se anche se appunto in realtà gli alberi non sono tantissimi. Anche in questo caso abbiamo analizzato anche la simulazione appunto di 20 anni dopo. Qui non si vede molto nel grafico però appunto l'inquinamento sembra appunto fermarsi ed effettivamente poi analizzando la simulazione successivamente si nota che qui l'inquinamento scenderà.
01:48:28 quindi
01:48:30 attraverso questo scenario abbiamo visto un'altra possibile soluzione del problema appunto diminuendo i fattori inquinanti del power plants mantenendo comunque il polluting rate abbastanza alto. Quindi a partire da questi scenari abbiamo analizzato insomma lo scenario desiderabile e a partire appunto da questi, vedendo dei risultati abbastanza ottimi, poi siamo partiti per l'analisi del backcasting [St4]. Lascio lascia la parola a M25 che appunto continuerà.

M25
01:49:08

SCENARIO DESIDERABILE

- aumento livello tecnologico,
- veicoli (dai macchinari agricoli e industriali ai mezzi di trasporto) non utilizzano più i combustibili fossili ma sono sia elettrici sia a idrogeno
- c'è una maggiore sensibilità riguardo il tema ambientale che viene molto più trattato a scuola, nelle industrie e sta a cuore a tutti
- c'è un aumento generale delle zone verdi dovuto anche al fatto che ogni 5 anni ogni persona pianta un albero

Come ha detto F21 ha come scenario desiderabile abbiamo tenuto conto delle varie parametri e li abbiamo ricondotti a delle cose reali. Come ad esempio il power plant, visto che sono quei fattori inquinanti, li abbiamo descritti come le fabbriche che facendo i loro lavori inquinano l'aria.
Comunque per lo scenario desiderabile dovremmo avere un aumento del livello tecnologico quindi ad esempio dei macchinari che non inquinano quindi macchinari che vanno con energia elettrica. Una maggiore sostenibilità anche diciamo a scuola. Negli istituti vengono fatti degli incontri che vanno a sensibilizzare gli studenti per avere una maggiore informazione a riguardo dell'ambiente. Poi appunto se andiamo nella prossima slide che appunto diciamo che lo scenario desiderabile è collegato molto al backcasting. [Dyn1]

BACK-CASTING

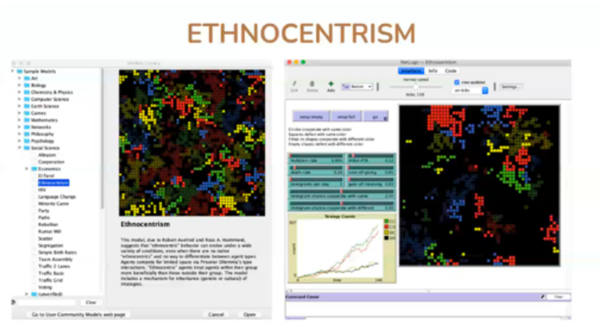
- industrie: accorpare più industrie che producono la stessa cosa in una sola in modo da ridurre i fattori inquinanti e gli sprechi
- sensibilizzare i cittadini: affrontare il tema nelle scuole, piantare gli alberi
- aiuti e incentivi statali per supportare il cambiamento verso tecnologie ecosostenibili
- veicoli: incentivare la produzione e l'acquisto dei veicoli elettrici o a idrogeno
- decidere regole, fare controlli capillari e multe e sanzioni per chi non le rispetta
- pareri contrari

Come soluzioni abbiamo deciso per arrivare a una soluzione del problema dell'inquinamento, abbiamo deciso di accorpare più industrie in una sola industria. Quindi nella Pianura Padana se ci sono diciamo 5 o 6 industrie che lavorano su uno stesso prodotto, abbiamo deciso di accorparle in una o due così da far sì che l'inquinamento viene meno, anche se magari là si lavora di più. Questo però ovviamente dev'essere incentivato dallo Stato dando comunque dei fondi per la creazione di materiali o veicoli che appunto non vanno più con i combustibili fossili ma vanno a idrogeno che non inquina, oppure con l'elettrico. Poi niente, se Martina ha qualcosa da aggiungere se no penso che comunque abbiamo detto un po' tutto quindi.

Group 6 – The last group (F26, M27, M28, M29, M30)

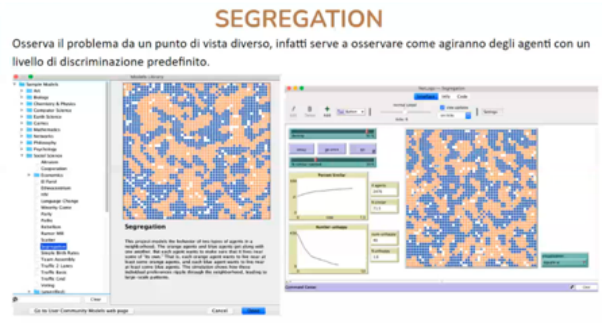
M30
01:54:23 Per il gruppo 6 presento io come rappresentante, preparo la condivisione dello schermo.
01:55:04 Il mio gruppo ha deciso di portare le discriminazioni razziali. In particolare abbiamo scelto questo tema perché lo troviamo ancora fortemente attuale. Pensiamo solo al movimento Black Lives Matter nato poco meno di un anno fa e che fino a qualche mese fa aveva ancora proteste molto intense.

01:55:32 Partendo da questo presupposto un po dalle indicazioni che ci sono state fornite allora abbiamo immaginato tre futuri molto semplici [Dyn7] che però sono abbastanza accurati.
01:55:47 In particolare abbiamo immaginato un futuro che potrebbe essere peggiore di questo pensiamo a una sorta di ritorno al passato,
01:55:56 che potrebbe essere una specie di imperialismo nazionalismi estremi oppure un altro futuro è un futuro simile a questo perché in fondo in vent'anni potrebbero anche non cambiare molte cose,
01:56:11 potrebbe risolversi un pochino il problema, potrebbe peggiorare un po' ma più o meno rimanere quello invece sarà il futuro.
01:56:21 Poi c'è il futuro che speriamo che tratterò nelle conclusioni.
01:56:26 In particolare abbiamo girato un po' fra le varie simulazioni presenti sul NetLogo però abbiamo deciso di parlare di due simulazioni in particolare perché sono quelle che trattano più strettamente il problema in particolare. Una che ci ha aiutato più o meno, una che invece non ci ha aiutato per niente.
01:56:48 Etnocentrismo e segregation.
01:56:53 Etnocentrismo è una simulazione che guarda come si evolvono le strategie di cooperazione degli individui all'interno di un gruppo in cui ci sono individui dello stesso tipo oppure immigrati che sono di tipo diverso che si distinguono per forma e colore.



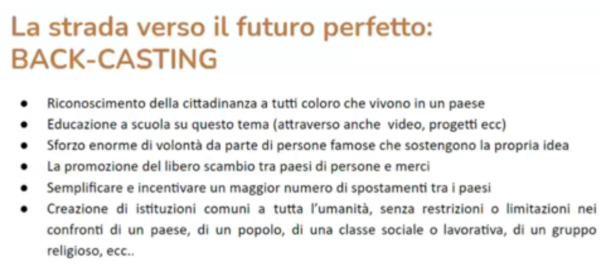
01:57:15 Tra queste ci sono ci sono appunto varie impostazioni come il cost of giving. Abbiamo osservato che è essenzialmente il costo che si dà per donare a qualcun altro. Infatti questa simulazione guarda a come gli individui si aiutano tra di loro.
01:57:35 Abbiamo analizzato che aumentando il cost of giving ma anche ciò che un individuo guadagnava da una donazione cresceva esponenzialmente il numero degli individui... non esponenzialmente ma molto... il numero di individui che non cooperavano con nessuno.
01:58:04 In generale la simulazione può essere utile per analizzare il problema perché in fondo guarda come le strategie degli individui si modificano in base a fattori esterni [St2].
01:58:17 Però ci sono due parametri come le possibilità che gli immigrati, che poi sono quelli che a lungo andare decidono davvero come si evolve la simulazione, collaborino con quelli dello stesso gruppo o con quelli di un gruppo diverso.
01:58:33 In questo modo diciamo è come se si mettesse una specie di livello di discriminazione già preimpostato che diventa un po' una difficoltà per risolvere questo problema ed il problema che abbiamo riscontrato nella simulazione segregation.

01:58:51 Essa infatti analizza come si comportano gli individui con un livello di discriminazione, se così si può chiamare, già predefinito in partenza.



01:59:10 In definitiva le simulazioni non ci hanno aiutato un granché nel trarre delle conclusioni, quindi siamo andati principalmente sulle nostre idee.

In particolare il futuro che ci eravamo immaginati sarebbe un futuro in cui ad esempio non viene più spesso specificata la razza nei telegiornali perché non è diventato più qualcosa che definisce davvero le caratteristiche di un individuo quindi non è più qualcosa che deve essere tenuto in considerazione, non è più qualcosa di importante allora possiamo anche iniziare a concentrarsi su concentrarci su problemi davvero importanti. In particolare ci sarebbe anche una maggiore apertura al dialogo e al confronto con culture e persone diverse. Probabilmente riusciremo anche ad accettare molte idee che noi ora non accettiamo portando anche a una maggiore tolleranza e quindi una maggiore libertà [Dyn3]. Ma di fronte a questo futuro utopico ci siamo chiesti come potremmo agire, come potrebbe agire l'umanità per riformare questo futuro senza discriminazioni anche se riteniamo che questi siano questi obiettivi sono poi irraggiungibili per il 2040.



Speriamo che in futuro possano essere raggiunti, come riconoscimento della cittadinanza a tutti gli individui che vivono in un determinato Paese e che pagano le tasse.
02:00:48 Se posso citare il motto della rivoluzione americana: Niente tassazione senza rappresentanza. Educazione a scuola sul tema delle discriminazioni perché discrimina questi temi s i combattono proprio con la diffusione di idee è l'unico modo in cui possiamo permettere una maggiore tolleranza non imponendo la forza per così dire.
02:01:17 Abbiamo identificato anche lo sforzo enorme di persone allo sforzo che devono fare persone famose che appunto possono aiutare questo dialogo. Questa diffusione di idee e allo stesso tempo anche la promozione del libero mercato di scambio tra persone e merci tra tutti i paesi del mondo. Basti pensare all'Unione Europea che ha portato al periodo di pace più lungo nella storia europea da un'Europa che prima era quasi perennemente in guerra.

02:01:51 Quindi da una maggiore libertà di movimento, semplificare e incentivare il maggior numero di spostamenti tra i Paesi, e infine la creazione di istituzioni...
02:02:04 L’ONU ne è un esempio però pensiamo a qualcosa di che possa entrare di più nella vita dei paesi, una sorta di federazione mondiale.
02:02:14 Si può dire anche per avvicinare l'umanità.
02:02:22 Grazie per l'attenzione.

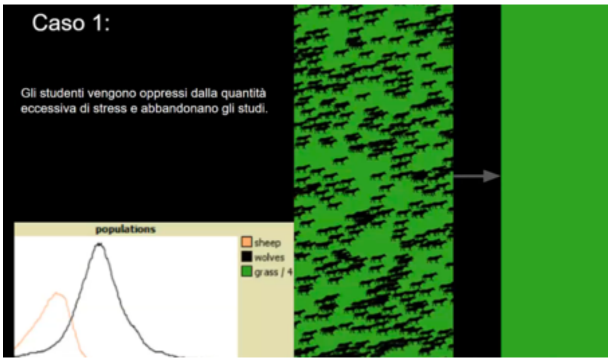
Group 7 - (F31, M32, M33, F34, M35)

F34

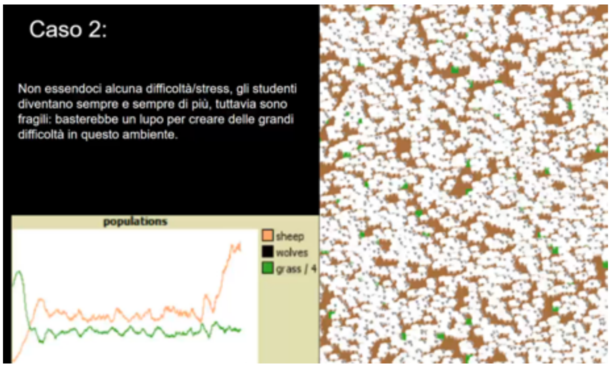
02:16 Noi abbiamo deciso di dividerci la presentazione tra di noi in modo tale che ognuno potesse presentare una parte del lavoro [St4]. E appunto abbiamo deciso di parlare della scuola nel futuro e in particolar modo del problema riguardante i livelli di stress a cui siamo sottoposti gli studenti nei percorsi di studi [St2]. Per trattare questa tematica abbiamo utilizzato come simulazione wolf sheep predation e all'interno di questa simulazione abbiamo identificato ciascun parametro ovvero lo stress gli studenti il tempo libero e li abbiamo identificati con una parte presente all'interno della simulazione e in questo caso abbiamo considerato i lupi come lo stress e le pecore come gli studenti e poi l'erba come il tempo libero che appunto gli studenti riescono a ritagliarsi nonostante i vari carichi di lavori. Dopodiché abbiamo analizzato tre diciamo scenari possibili che illustra M32.

M32

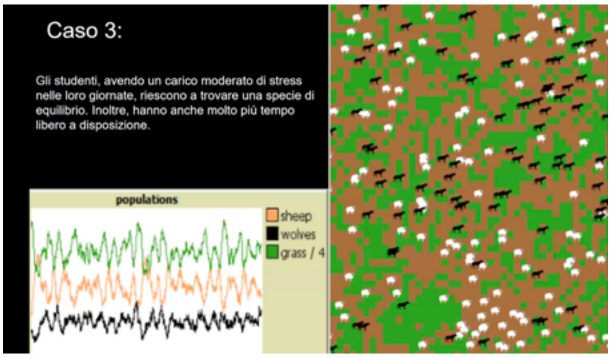
03:32 Spero che si veda ancora perché ho dovuto aprire il microfono e allora io presenterò velocemente tre casi che abbiamo considerato per capire come potrà essere la scuola del futuro del 2040 usando questa simulazione [Dyn7]. Per quanto riguarda il primo caso ci siamo messi questa ipotesi ovvero che lo stress sia talmente alto da fare in modo che quasi tutti gli studenti abbandonino gli studi [St3]. E ovviamente già dalla simulazione possiamo capire che la popolazione degli studenti inizierà a calare, calare, calare invece lo stress alla fine rimarrà a dominare su nessuno perché se non ci sono studenti ovviamente lo stress non può agire su nessuno.



Invece il secondo caso è quello dove non c'è alcuna difficoltà, alcuna fonte di stress e quindi gli studenti cosa fanno? Diventano sempre di più. Tuttavia basta una piccola cosa una piccola difficoltà che crollano. Infatti basta un lupo in un gregge di pecore come per esempio questa immagine, e ovviamente il lupo... Possiamo già capire le conseguenze che potrà creare [St3].

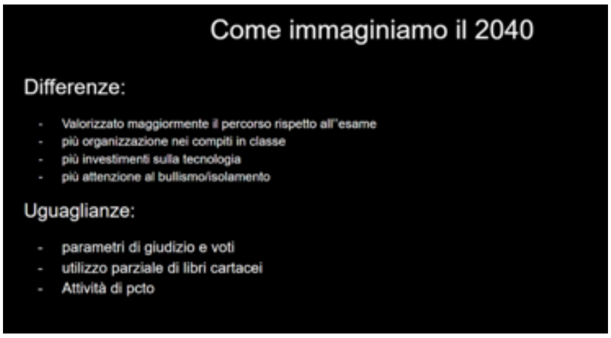


Invece nel terzo caso e abbiamo deciso di vedere per esempio come integrare gli studenti e il tempo libero con anche lo stress. Infatti, si può vedere qui che la popolazione di studenti o comunque anche il tempo libero e lo stress seguono un andamento quasi periodico e stanno in equilibrio. Quindi gli studenti a volte magari possono avere delle fonti di stress quindi magari i progetti da fare lavori da eseguire. Però tuttavia continuano ad avere anche molto tempo libero a disposizione e quindi sono anche formati per poter continuare ad andare bene nel lavoro che trovano e che fanno [Dyn5].



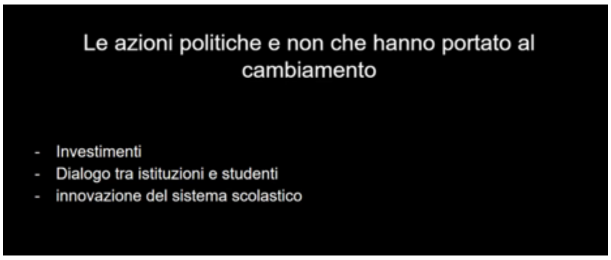
05:45 E quindi andando avanti vedremo come abbiamo immaginato il 2040, la scuola del 2040.

M33
05:56 Per mantenere questo equilibrio nel 2040 tra lupi e pecore abbiamo pensato diversi cambiamenti e a diverse cose che devono rimanere invariate all'interno di questo sistema. Una fonte di stress, come sappiamo, per tutti gli studenti è il risultato finale di quel percorso ovvero quello dell'esame e attualmente sappiamo come le prove dell'esame influenzano molto nella valutazione finale e quindi abbiamo pensato di favorire maggiormente il percorso che viene svolto in tutti gli anni scolastici rispetto a solamente l'esame finale. Inoltre, anche nei compiti in classe i compiti in classe suscitavano molto stress all'interno cioè per gli studenti e quindi è necessaria una maggiore organizzazione non solo per quanto riguarda gli studenti stessi nel prepararsi in questi compiti ma anche tra gli insegnanti che dovrebbero cercare di distribuire in maniera migliore il carico di lavoro. Abbiamo pensato anche che per migliorare lo studio degli studenti è necessario investire sulla tecnologia. Già in questo periodo la tecnologia sta prendendo piede all'interno di tutte le scuole ma pensiamo che si può migliorare ancora su questo aspetto. Ed infine un'altra fonte di stress è appunto quello che può essere il bullismo e quindi fare più attenzione appunto a situazioni in cui ci possono essere ragazzi soggetti a questo tipo di eventi. Però pensiamo anche per mantenere questo equilibrio è necessario mantenere alcuni parametri invariati, come per esempio i giudizi e i voti che servono per dare anche sprono agli studenti nel restare diligenti e continuare a lavorare costantemente. Un utilizzo parziale dei libri cartacei perché? Questo va un po' in contrapposizione con quello che abbiamo detto prima però pensiamo che, comunque sia, mantenere una parte dello studio sui libri sia necessario perché i libri possono dare alcune possibilità in più allo studente di organizzare lo studio [Dyn2]. E infine anche le attività PTCO che pensiamo siano molto importante perché danno allo studente possibilità di applicare le proprie conoscenze fuori dall'ambito solo scolastico.



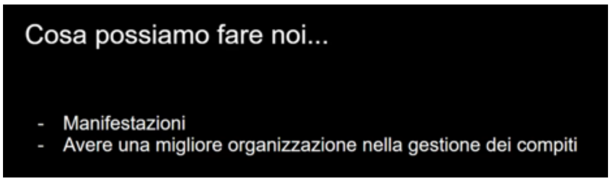
Quindi adesso vedremo le azioni politiche e non solo che portano a questo cambiamento nel 2040.

F31
08:46
Allora dopo la pandemia le persone si sono accorte di quanto sia stata gestita male la scuola a causa delle indicazioni incerte che arrivavano sempre in ritardo e successivamente grazie alle manifestazioni e alle sollecitazioni degli studenti le loro idee sono state prese in considerazione dagli adulti. Queste manifestazioni hanno reso possibile un maggiore dialogo tra istituzioni scolastiche e studenti. Anche l'attenzione da parte del governo verso la scuola è aumentata infatti sono stati fatti degli investimenti finanziari. Infine, grazie a questi investimenti c'è stata un'innovazione del sistema scolastico, delle scuole e delle attrezzature. Sono cambiate tutte le cose che abbiamo detto prima.



M35

10:05 In conclusione, dovremmo vedere quello che possiamo fare noi per migliorare la situazione [Dyn3]. Abbiamo individuato due principali azioni che noi possiamo fare per migliorare la situazione per manifestare sia in senso stretto proprio le manifestazioni organizzate di cui si parla molto ultimamente e anche una manifestazione in senso più lato nel senso manifestare personalmente o anche a livello di classe i propri pensieri alla scuola. Quindi incoraggiare un dialogo tra gli studenti e professori e l'organizzazione scolastica. E la cosa finale e che forse non la più importante è la gestione da parte degli studenti nella loro autonomia dei compiti e dei progetti che devono svolgere [Dyn3] perché si può manifestare finché si vuole, si può avere un sistema scolastico perfetto però comunque bisogna adoperarsi e bisogna fare il lavoro per ottenere dei risultati [Dyn4].



Appendix H – Transcripts of two groups' presentations with codes for school-related macro-themes

Group 4

Phase of the activity	Transcript	Word count (of the Italian transcript)	Macro-themes
Intro	Change the school! So as a method of presentation we have chosen to create an Instagram page in which we have inserted five posts regarding our theme. Now if you want I can also send links to the page so that you can all access it.	37	no code
Statement of the problem	So the problems we have focused on are inherent to school and there are two. The first, the main one, concerns the teaching method.	24	knowledge
	The second is the type of votes.	7	anxiety
	We believe that the classical notional and frontal teaching method is boring and not very interactive and to make it better, let's say we should make more use of digital devices in the classroom.	16	knowledge
	and to make it better, let's say we should make more use of digital devices in the classroom.	15	technology
	It is a fairly current issue because we have been at home for many months with the Covid issue.	17	pandemic
	And the technology turned out to be quite useful, indeed a lot. Technology is certainly a good teaching and learning tool, if clearly combined with paper and therefore with books.	30	technology
	Another point on which we have focused is the question of school grades which we have noticed that let's say they put a little difficulty in the boys. We are therefore not speaking of a total abolition but of a passage from votes expressed in numbers to votes expressed in letters of the alphabet, as is the case in America for example.	55	anxiety
	This is a bit of the description of the post regarding the problem. Now I leave the floor to Francesca that she will talk about the simulations we used.	24	no code
Choice of the simulation	Among the various simulations that we thought could soon reproduce this issue of ours, we chose cooperation because in our opinion it was more suited to this topic. So as agents we have chosen the greedy cows As we say those who support the old traditional teaching methods, as instead the cooperative cows all those who support anyway I want to carry on new teaching and learning methods like the grass in fact we thought that it could be the support, the support from the students. So we have already seen the mechanism in previous lessons. However, we have explained it in this way, that is to say that both, both the greedy ones and the cooperative ones, are nourished by the support of the students. However, while collaborative cows tend to carry out their own initiatives by supporting the will of the students and adapting accordingly, for example they do not want to impose themselves on the students but prefer to have the necessary support to have the funding deriving precisely from the support of the students. students to carry out their own changes. But they do not want to impose themselves but perhaps leave a part of the students, as if there were, let's say, the support - I don't know who has already studied Aristotle - in potentiality that becomes active with the funding, so that this process of comparison and change can continuously move forward making sure that the school can always be at the forefront of new technologies, etc.	371	no code

	Here, however, the other cows impose themselves on the students in this way, they try to get all the support of the students and therefore also lower future support, new and perhaps initiatives and therefore prevent students from confronting each other, perhaps obtaining a school that can adapt. more to their new needs. Then, let's say, we attributed some meanings to the variants… well, for example, the cost of reproduction as a cost necessary to carry out new initiatives. Then we chose as we have already established that surely the number of greedy cows will be greater than that of cooperative cows. Then, for example, I do not know that precisely the energy of the grass was therefore the financing by the students. The metabolism that with each action the cows, both the greedy ones and the collaborative ones, lost parts of their energy and so let's say their money maybe kept aside.		
Scenarios with the simulation	From this simulation we have found that the possible scenarios that we are going to deepen even more in practice could be: the most desirable is the balance between the old traditions and instead those old teaching methods the more innovative ones because we think that both they can be useful and fundamental in reality to reach a type of school, of modern teaching more suitable for students. The other two are more to say the extremes, that is, only the new teaching methods prevail and therefore can, let's say, abandon some modalities that are useful for teaching and perhaps increase the risks due to new technologies. And instead on the other hand we have therefore the lack of imposition: the new methods fail to impose themselves in schools and therefore we do not get this other but this change. And then we started from the fact that a possible solution of the simulation that can then be applied in reality is that the cost of reproduction could be lowered. For example, in practice this can amount, for example, to ensuring that the government can bear the costs necessary for new changes and thus making it easier and faster to implement new methods within schools. I pass the word to my colleague who will instead tell us the possible futures.	222	no code
Ideal scenario	We have analyzed that in the course of this pandemic	8	pandemic
	the use of technologies is becoming more and more common. In particular, we also considered how probably these new technologies will tend to become almost everyday life, perhaps even starting from middle school. In fact, we have considered the use of technological tools starting from the most elementary schools precisely because spending many hours in front of screens from an early age can also lead to posture defects or even damage health and therefore there will most likely be strong opposition. which will also limit the use of technology with regard to the first years of school and therefore will probably reach a level in which electronic devices such as computers and tablets will also be used with a good sequence during lessons starting from middle school, in our opinion.	130	technology
	In particular we were also imagining a possible platform that allows a better synergy so that the teacher can also enter the work of each student to see in real time what he is doing, also allowing to better understand the reasons for which maybe he's stuck in a problem and then can't move forward.	60	technology
	Furthermore, we also imagined that new teaching methods adapt to a new management of times that for us needs to be improved a little.	25	routine
	In fact, the lessons seem to us perhaps too dense and therefore very often it becomes difficult to be able to better grasp all the notions that are provided to us.	27	knowledge
	So we also imagined perhaps longer lessons that contain the same amount of information so that the latter are diluted over time.	26	routine
	Obviously we realized that in addition to being the possible solution to shorten the training plan, perhaps by removing some more nationalistic elements that will then be forgotten,	29	knowledge
	it could also be convenient to use in the afternoon	8	routine
	so that we can also organize hours in which students can meet to do group study, perhaps even with some professors.	26	relationship
	We have also noticed that in this way the time available could also grow exponentially because a quality study would be made that would allow us to reduce the time to devote to self-study. But this will then be better narrated by our companion.	41	routine

	Immediately after we also noticed how having the afternoons available to students seems even more incentivized to take courses that could also lead them to approach experiences that they have never done in their life and in doing so they could also have a better idea of which may be their attitude. It could also be useful for orienting them to a university course.	64	knowledge
	In addition, spending so much time in school also becomes necessary for physical activity. Consequently we have also imagined a future in which schools organize sporting moments even within the lessons as happens for example in America with basketball ... we know precisely that the teams are specific to the school and therefore it could also be useful to favor the part concerning the motor aspect.	63	routine
	Furthermore, with the increase in returns to school, human relationships would be favored both between students and between professors and students, making sure that we also go to re-evaluate what is our image of the teacher who otherwise is seen as an austere character who wants put us in difficulty only when in reality the latter is still a person who perhaps shares our same interests and a better bond could also be created.	74	relationship
	Furthermore, we also imagined that in the future school trips or internships could become more and more present to acquire new knowledge much more varied than those that can be learned at school.	36	knowledge
	We also paid particular attention not to imagine a future that would require large funds from the state because we realized that it would take much longer to implement them all within our future and consequently, apart from what concerns new technologies, we imagined a future that was achievable even without large funds.	60	technology
	Yes then I say we tried to imagine what a day could be for us students in our best future, in case all our projects went in the best way. So we thought that in the morning there could be lessons like now but from 9 to 13 so do 4 hours ... so start a little later than now ... okay let's leave the situation of the virus alone that in our ideal future our ideal day should already the pandemic is over, so let's imagine a normal day without viruses. So four hours of lessons for all that end at 13 hours in which it begins with a lunch break that can be used to eat but also to rest.	122	routine
	And then in the afternoon we thought that going back to school could actually be very useful. Clearly the lessons in the morning are less notional lessons but lessons in which things are taught but there is also a lot of talk about the material application	41	knowledge
	because then in the afternoon at the time from about 2:30 pm to 5:00 pm ... then it is clear that we have given a bit of an image but then objectively you can change it and you can think for a moment how to do it better ...	36	routine
	however during these hours laboratory activities or meetings with experts can be carried out with visits such as trips or visits for example to museums	26	knowledge
	and precisely for example the sporting discourse which today objectively is almost an obstacle to sporting life outside of school for a student ...	23	routine
	so let's say that these are all activities that in the afternoon it is important to do in my opinion as well as for example a collective afternoon study among au pairs or even with professors. In this way the human relationship is valued and we move further away from a concept of frontal teaching but a teaching that aims more at education in itself and less at objectively you know the things that are then often forgotten many notions.	73	relationship
	Then precisely from 5 pm, let's say the most personal activities can begin. So if one needs further study, he can study again or he can already begin to rest or carry out his fun and relaxation activities. This is an aspect that we think there is little today, time for oneself today is a bit neglected because in any case we are always busy with questions and checks at least during the year. Maybe even the management of the school timetable as it is distributed throughout the year ... maybe avoid leaving three summer months but dividing it better could be very functional. And then the evening is time to dedicate to friends or family which is increasingly important in life. This is a bit like our ideal day. For the conclusions I pass the floor to my colleague.	133	routine
Back-casting	Then I will mainly talk about the main problems and what we can do. First of all, support is needed from the government, from the Ministry precisely to increase funds for schools, to set up schools or projects that individual schools cannot do.	45	no code

	For this it is necessary in a sort of activism on the part of students and teachers who can therefore make petitions or even movements on social media to the mass media. In this way, many more people would come into contact with this thought and maybe it would also spread the fastest way since we can exploit a tool that is still very prevalent today in the life especially of young people.	71	agency
	Then there would be the objection that the school curriculum should not be curtailed. To cope with this problem, innovative schools could be set up scattered throughout Italy in order to obtain data that can actually be compared to those that exist now with traditional schools. In this way it could be argued that the school program is already ideal as it is now, when it can be changed and needs to be changed.	77	knowledge
	Furthermore, it is also difficult to find teachers willing to try new teaching methods. In this case, projects or courses could be set up for the teachers themselves so that they have the opportunity to discuss with each other to devise new teaching methods and perhaps even discuss them with the students in order to have their approval.	59	agency
	Another important point is peer teaching, something that is already present now but is not being exploited enough. In fact, most of the students who join these projects do it for personal remuneration, therefore as school credits, and do not actually think about how effective these opportunities are. For this it would be useful to publicize these events and make them common in all schools.	63	relationship
	Finally, an effort is needed on the part of everyone, especially the students. In fact, it is the students themselves who mobilize themselves to bring about a change in Italian education. For this it is necessary to awaken in a certain sense the students from the passivity that lies in these days, in this period. More than passivity I would say indifference towards the school, since now it is almost like torture many times. For this we need movements that can reach everyone, so that they realize that the school can change and they can do something to help.	98	agency

Group 7

Phase of the activity	Transcript	Word count (of the Italian transcript)	Macro-themes
Introduction	We decided to divide the presentation between us so that everyone could present a part of the work.	21	no code
Statement of the problem	And in fact we decided to talk about the school in the future and in particular the problem concerning the stress levels to which students are subjected in their studies.	31	anxiety
Choice of the simulation	To deal with this issue we used wolf sheep predation as a simulation and within this simulation we have identified each parameter or stress the students leisure time and we have identified them with a part present within the simulation and in this case we have considered the wolves like stress and sheep like students and then grass like free time that students manage to carve out despite the various loads of work. We then went through three let's say possible scenarios that Catalin illustrates.	86	no code
Scenarios with the simulation	I hope you still see why I had to open the microphone and then I will quickly present three cases that we have considered to understand what the school of the future of 2040 will look like using this simulation. As for the first case, we put this hypothesis into place, namely that the stress is so high that almost all students drop out of their studies. And obviously already from the simulation we can understand that the student population will begin to decline, decline, instead stress will eventually dominate anyone because if there are no students, obviously stress cannot act on anyone. Instead, the second case is where there is no difficulty, no source of stress and so what do the students do? They become more and more. However, a small thing is enough a small difficulty that they collapse. In fact, just a wolf in a flock of sheep such as this image, and obviously the wolf ... We can already understand the consequences that it can create. Instead in the third case and we decided to see for example how to integrate students and free time with stress. In fact, it can be seen here that the student population or in any case also free time and stress follow an almost periodic trend and are in balance. So the students sometimes may have sources of stress so maybe the projects to be done work to be carried out. However, however, they also continue to have a lot of free time available and therefore are also trained to be able to continue to do well in the work they find and do.	268	no code
Ideal scenario	And then moving forward we will see how we imagined 2040, the school of 2040. To maintain this balance in 2040 between wolves and sheep we have thought about several changes and several things that must remain unchanged within this system.	40	no code
	A source of stress, as we know, for all students is the final result of that path or that of the exam and we currently know how the exam tests greatly influence the final evaluation and therefore we decided to favor the path that is carried out more. in all school years compared to only the final exam.	54	anxiety
	In addition, even in the classroom assignments the classwork caused a lot of stress inside i.e. for the students and therefore greater organization is needed not only with regard to the students themselves in preparing for these tasks but also among the teachers who should try to better distribute the workload.	55	anxiety

	We also thought that to improve students' study it is necessary to invest in technology. Already in this period the technology is taking hold in all schools but we think that there is still room for improvement in this aspect.	39	technology
	And finally another source of stress is precisely what bullying can be and therefore pay more attention to situations in which there may be children subject to this type of events.	34	anxiety
	But we also think to maintain this balance it is necessary to keep some parameters unchanged, such as the judgments and grades that are also used to encourage students to remain diligent and continue to work constantly.	37	anxiety
	Partial use of paper books why? This goes a bit in contrast with what we said earlier but we think that, in any case, keeping a part of the study on books is necessary because books can give the student some more possibilities to organize the study.	48	technology
	And finally also the PTCO activities which we think are very important because they give the student the possibility to apply their knowledge outside the school only.	25	knowledge
Back-casting	So now we will look at the political and other actions that lead to this change in 2040.	16	agency
	Then after the pandemic, people realized how badly the school was managed due to uncertain indications that always arrived late	27	pandemic
	and later, thanks to the demonstrations and requests of the students, their ideas were taken into consideration by adults.	20	agency
	These events have made possible a greater dialogue between educational institutions and students. The attention from the government towards the school has also increased in fact financial investments have been made. Finally, thanks to these investments there has been an innovation of the school system, schools, and equipment. All the things we said before have changed.	56	pandemic
	In conclusion, we should see what we can do to improve the situation.	13	agency
	We have identified two main actions that we can do to improve the situation to manifest both in the strict sense precisely the organized events that are talked about a lot lately and also a manifestation in a broader sense in the sense of manifesting one's thoughts personally or even at a class level. to the school.	52	agency
	So encourage a dialogue between students and professors and the school organization.	12	relationship
	And the final thing and perhaps not the most important is the management by the students in their autonomy of the tasks and projects they have to carry out because it can manifest as long as you want, you can have a perfect school system but in any case you have to work and you have to do the work to get results.	56	agency