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The Quest for Product Safety in the Context of 3D Printing: A Law and Economics Analysis

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The Quest for Product Safety in the Context of 3D Printing: A Law and Economics Analysis

De zoektocht naar productveiligheid in de context van 3D-printen: Een rechtseconomische analyse

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To my parents

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List of Abbreviations

ALI American Law Institute

AM Additive Manufacturing

AMAC Additive Manufacturing Association of China

AMP Advanced Manufacturing Partnership of the US

CAD Computer-Added Design

CAMT China Additive Manufacturing Product Quality Testing Center

CDLP Continuous Digital Light Processing

CEN European Committee for Standardisation

CSGD European Consumer Sales and Guarantee Directive (1999/44/EC)

CSD European Consumer Sales Directive (2019/771/EU)

DMLS Direct Metal Laser Sintering

DLP Digital Light Processing

DOD Drop on Demand

EBM Electron Beam Melting

EC European Commission

ECRD European Consumer Rights Directive (2011/83/EU)

EDCD European Digital Contract Directive (2019/770/EU)

EEC European Economic Community

EPLD European Product Liability Directive (86/374/EEC)

EU European Union

FDM Fused Deposition Modelling

FoP-PPP Factories of the Future Public-Private Partnership

FP Framework Programmes

FTA Food and Drug Administration of the US

GDPR General Data Protection Regulation

IDD. Insurance Distribution Directive

IoT	Internet of Things
ISO	International Organisation of Standardisation
KET	Key Enabling Technologies
LOM	Laminated Object Manufacturing
MOTIE	Ministry of Trade, Industry and Energy in Korea
MDR	European Medical Device Regulation (2017/745/EU)
MJ	Material Jetting
MJF	Multi-jet Fusion
NAMIC	National Additive Manufacturing Innovation Cluster in Singapore
NCDMM	National Center for Defense Manufacturing and Machining in the US
NIIAM	National Innovation Institute of Additive Manufacturing in China
NPJ	Nanoparticle Jet
PPP	Public-Private Partnership
R&D	Research and Development
SAMR	State Administration for Market Regulation in China
SASAM	Support Action for Standardisation in Additive Manufacturing in UK
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SME	Small and Medium-sized Enterprise
UAM	Ultrasonic Additive Manufacturing
USPTO	United States Patent and Trademark Office
WIPO	World Intellectual Property Organisation

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INTRODUCTION

Background and Motivation

He who fights with monsters might take care lest he thereby becomes a monster. And when you gaze long into an abyss the abyss also gazes into you.

—Friedrich Nietzsche, Beyond Good and Evil

When Karl Benz invented the world's first petrol-powered car in 1885, he probably did not foresee the first car accident six years later in 1891, and the thousands of deaths that subsequently followed; or that car manufacturers would run the risk of being found liable.

A great invention always has two sides. One represents glamour, promising an improvement in society, while the other represents the harsh reality that no revolution is painless. Where value is created, risk becomes inevitable. This dichotomy leads stakeholders to try to find a balance. The idea behind achieving this balance is sobering – people often choose the strategy that benefits them the most, conditioned by the environment and the decision-making of others.

Production also has its own complex dynamics. The moment an individual seeks to trade a product for another, the parties involved have to find ways to allocate risk. In the context of pre-industrial societies, both parties were supposed to find a balance through their own efforts. Since the Industrial Revolution and the adoption of disruptive technologies, however, this equivalence has gradually diminished. The adoption of technologies makes production an increasingly professional career. Due to the economies of scale, not every party can step into this realm. Therefore, consumers, who are placed in an inferior position, appealed for measures that could protect them from disproportionate risks. Thus, the evolution of production reflects not only the extent to which people are exposed to product risk but also the variance in the allocation of product risk between the parties who are involved in production.

Currently, the production industry is witnessing a new round of the Industrial Revolution, which is driven by the Internet of Things (IoT), cloud computing and big data, as well as other forms of disruptive technologies. One of these technologies, 3D printing, has significantly shifted the method of production. In many ways, 3D printing is a form of digital manufacturing: the final physical product is printed from a digital format.

From a technical perspective, 3D printing achieves the interaction between the digital and physical worlds. Applying 3D printing in the production sector could have far more impact than its technical specification might imply. With the adoption of 3D printing, cost per unit is no longer the most important element to distinguish between producers. Rather, a competitive business would be one that could offer a wide range of products. Another important disruption caused by 3D printing is that it significantly lowers the threshold of engaging in production activities, meaning that people with different levels of knowledge can engage in activities at different levels. Production, therefore, is no longer an activity in which only professional producers can participate. Besides, with the adoption of 3D printing, consumers are far more proactive than they normally are with mass production, since they have to self-direct the process of production by coordinating parties from various sources. In other words, consumers serve as the party to choose the way of digital designing and to determine the approach of printing.

The fact that the whole production process is accomplished by two separate parties and that non-professionals are increasingly engaging in production implies that risk generated within the process of 3D printing seems inevitable.[1] As such, this research mainly focuses on the product risk generated in the context of 3D printing.

Research Questions

This study aims to understand the institutional approaches to improving product safety in the context of 3D printing. Accordingly, the main research question is:

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[1] Some of the literature that paid attention to the risk generated by 3D printing include: Engstrom, Nora Freeman. "3-D printing and product liability: identifying the obstacles." U. Pa. L. Rev. Online 162 (2013): 35; Berkowitz, Nicole D. "Strict liability for individuals-the impact of 3-d printing on products liability law." Wash. UL Rev. 92 (2014): 10; Reddy, Preeta. "The legal dimension of 3D printing: Analyzing secondary liability in additive layer manufacture." Colum. Sci. & Tech. L. Rev. 16 (2014): 222; Harris, Allison. "The Effects of In-home 3D Printing on Product Liability Law." Journal of Science Policy & Governance (2015); Lindenfeld, Eric. "3D Printing of Medical Devices: CAD Designers as the Most Realistic Target for Strict, Product Liability Lawsuits." UMKC L. Rev. 85 (2016): 79; Beck, James M., and Matthew D. Jacobson. "3D printing: what could happen to products liability when users (and everyone else in between) become manufacturers." Minn. JL Sci. & Tech. 18 (2017): 143; Howells, G. "Protecting consumer protection values in the fourth industrial revolution." Journal of Consumer Policy (2020): 1-31.

Regarding the product risk generated with the adoption of 3D printing, how can various legal instruments be used to maximise social welfare by appropriately reducing accidents and spreading the risk?

To answer this question, a number of sub-questions are asked and addressed in this research.

The first sub-question (Q1) is: *to what extent does 3D printing as a way of production differ from the traditional mass production, and what do these disruptions mean for product safety?* This sub-question aims to delineate the technical and social disruptions caused by 3D printing. The study reveals how 3D printing as a way of production differs from traditional mass production, especially when production is organised in a way that digital modelling and physical fabrication are respectively undertaken by different parties, with the whole process coordinated by consumers.

Having shown the disruptions caused by 3D printing, the follow-up issues relate to the quest for the efficiency of various legal instruments to optimise the behaviour of relevant parties and to spread the risk. Therefore, the second sub-question (Q2) is: *to what extent can contractual parties reach an agreement to efficiently reduce accidents and to spread the risk over contractual parties?* Further, sub-question three (Q3) relates to tort liability, which is: *to what extent can tort liability rules incentivise parties to behave appropriately and help risk-averse parties to shift risk?*

Finally, this research turns to other complementary instruments, which could also contribute to the goal of deterrence and risk-shifting in the context of 3D printing. The typical instruments are regulations and platform governance. The fourth sub-question (Q4) asks: *how can regulators and platforms take measures to improve the effect on deterrence and risk-spreading?*

Methodology

Law and economics methodology as the analytical and predictive framework

Law and economics analysis as a methodology can provide tools at both the analytical and predictive levels. By introducing the concept of social welfare, the positive and normative questions become testable. Specifically, the performance of an instrument can be tested by measuring the increase or decrease in social welfare in a particular scenario. Also, social welfare provides a framework for predicting and comparing the performance of various instruments.

Having chosen social welfare as the benchmark to answer the positive and normative questions, the next core issue is what elements should be used to *measure* social welfare. According to welfare economics, the scope of social welfare can be very broad. It covers all elements relating to the well-being of individuals (i.e., the utilities), ranging from economic factors (e.g., the gains from production and consumption) to the notion of fairness.[2]

Taking production as an example, social welfare can primarily be tested by counting the utilities that are generated by production and consumption. In particular, the utility of producers will increase as they engage in production activities, and the utility of consumers will increase as they purchase a product. However, considering the potential risk embedded within the product, these utilities could be reduced when the efforts invested in *precautions* and the *damage* caused by the product are included. On this issue, social welfare is measured by aggregating the total gains and losses that are perceived by the parties. The maximum of the total utilities would be achieved at the margin, where the cost per unit of consumption starts to be higher than the wealth per unit gained by the relevant parties. The socially optimal equilibrium point is what people should pursue.[3] If an instrument can induce relevant parties to behave in this optimal way, this instrument would be regarded as efficient. As a result, deterrence is the primary goal in dealing with accidents.

In reality, parties can be risk-averse to some extent. Whenever this is the case, social welfare is measured not only by the cost of accidents but also by whether the risk-averse parties can escape from bearing the risk.[4] If the risk-averse parties can avoid the risks, their expected utilities will correspondingly increase. In sum, risk-spreading serves as another crucial benchmark to assess the efficiency of a legal instrument.

Apart from the wealth determined by deterrence and expected utility regarding risk preference, *fairness* which relates to distributional equity and corrective compensation also serves as a crucial facet for determining the desirability of an institutional design.[5] However, law and economics scholars typically exclude the elements relating to distributive justice and corrective justice from

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[2] Shavell, Steven. FOUNDATIONS OF ECONOMIC ANALYSIS OF LAW. Harvard University Press, 2004, at 2 and 596.

[3] Id., at 207-223.

[4] Id., at 257.

[5] Id., at 2-3.

the criteria that are used to measure social welfare. It is not because these factors are unimportant, but simply because including them into the evaluation will complicate the discussion.[6] As additional transfer instruments can be offered in respect of the social welfare relating to the issues of distribution and compensation, any unfair distribution or compensation could be offset by these instruments.[7] As a result, the question of compensation is separate from assessing the social welfare aspect of an instrument.

This research project follows the roadmap adopted by traditional law and economics, which means that measurements based on deterrence and risk-shifting will provide the criteria to test the efficiency of a specific instrument and to predict its performance. Therefore, the issue of compensation is beyond the scope of this research.

Moreover, this research is built upon a rational choice model, meaning that the analysis and pertinent recommendations are based on the assumptions that sellers and consumers are expected to make decisions aligned with the maximised utilities under given conditions. In recent years, the rise of behavioural analysis has shown that, due to multiple reasons such as endowment effect, altruism and time preference, people may not behave in a way that ultimately maximise their utilities. This research does not address these complicated scenarios. Instead, its main objective is to study the behaviour of stakeholders conditioned by the adoption of 3D printing in different business models. Notably, this research will pay closer attention to how various legal instruments could incentivise stakeholders to behave optimally.

Instrumental mix

To date, the complexity of accidents and the variety of the parties involved implies that it is not an easy task to rely on a single instrument to achieve the socially optimal goal. In theory, externalities can be solved efficiently through private bargaining.[8] However, this result is based on a number of assumptions; some key ones are that no transaction cost or information cost is present, that contractual parties are risk-neutral and that the market is competitive. In reality, where these

[6] Id., at 3.

[7] Ibid.

[8] Coase, R. H. "The Problem of Social Cost." The Journal of Law & Economics 3 (1960): 1-44.

assumptions have become relaxed, relying on a single instrument might not result in the expected outcome.

In theory, an instrumental mix is necessary at two levels.

Firstly, an instrumental mix is desirable when it comes to reducing accidents. In reality, optimal deterrence might not be provided by a single instrument. For example, since consumers may hold asymmetric information when they conclude a contract with the producer, some risks might not be reflected in the contract; thus, contracting over product risk may not induce producers to take optimal precautions. In such situations, additional instruments are necessary to provide extra incentives for relevant parties to behave appropriately, while providing social welfare. Traditionally, we rely on contractual relationships and tort liability to achieve appropriate behaviours from parties. In the context of 3D printing, we can also rely on additional instruments, such as regulations and other new methods (e.g. platform governance and codes), to achieve the goal of deterrence.

Secondly, we need additional instruments to achieve the goal of risk-spreading. For example, the instrument through which risks are allocated to the party that can reduce accidents at the lowest cost might not be the instrument that meanwhile allocates the risks to the party that is the least risk-averse. In this sense, one single instrument might not achieve the goal of deterrence and risk-shifting simultaneously. To address this challenge, instruments that could prompt mutually appropriate behaviours must be adopted to achieve the goal of deterrence, while additional instruments must be employed to correct the inefficiencies related to risk-shifting. Diverse instruments could be used for spreading and shifting risk. Apart from contractual relations and tort liability, insurance as a particular risk-spreading instrument is commonly accessible to relevant parties.

Having set up the goals pursued to deal with product risk, people may realise that it is possible that a single instrument may play a role in all aspects (i.e. deterrence and risk-spreading). However, it is highly possible that an instrument is superior in one aspect but far less competent in other aspects. Considering the difficulties of one instrument to achieve all these goals, a mix of instruments is necessary. Therefore, in a given situation, we need to first check the extent to which one specific instrument can achieve our goal (either deterrence or risk-shifting) compared to others. Additional instruments should also be carefully examined to improve social welfare.

3D printing from an European perspective

In the context of 3D printing, production is even more democratised and decentralised in comparison to conventional mass production. A design may be accomplished and uploaded by a party in one country, further printed out by a different party from another country, and causes harm in a third country. The situation could be even more complicated in an open-source environment, where a digital design is remixed by users from a dozen countries in sequence. In this scenario, everyone from the supply chain should be provided with an incentive to behave appropriately. If these parties come from different countries, and the laws from these countries are quite different regarding liability or compliance, it will finally induce parties from various countries to behave differently.

In the EU production sector, a directive or regulation comes typically into force to facilitate the free movement of products and services among different Member States and ensures that producers across the EU are provided with an incentive to behave appropriately. In practice, the EU laws can be transplanted into domestic laws differently by various Member States, primarily when the directive or regulation provides no further clarification on a particular issue. This research will focus on EU directives and regulations to see whether they can incentivise parties to behave in a manner consistent with the goal of maximising social welfare. Where EU laws provide no guidance and the clarification of issues resides with Member States, a comparative analysis would be conducted. By doing so, the interpretation accorded to issues at national levels and the extent to which one pattern results in better social welfare than another will be discussed.

The Structure of the Dissertation

To address the research questions, this dissertation is structured into four content parts, which can be further subdivided into ten chapters.

Part I. The disruption of 3D printing: a technical and social perspective

Part I mainly explains how 3D printing disrupts the sector of production and generates new product risk that should be of concern. Three chapters are included in this part.

Chapter 1 introduces the technical disruptions that have accompanied the adoption of 3D printing. A complete 3D printing process can be divided into two steps: digital modelling and fabrication. The chapter demonstrates that the main function of a physical product is decided in the digital modelling stage, so the computer-aided design (i.e. the CAD file) has a substantial impact on the quality of the product. Fabricators must follow the instructions set by digital designers.

Chapter 2 introduces the stimulus of 3D printing from industrial and policymaking perspectives. It reveals that 3D printing has been widely applied in various sectors, ranging from mechanical tools to medical devices. Also, many countries have developed national strategies in support of the domestic development of 3D printing.

Chapter 3 explains the value created and risk posed by 3D printing. From the value creation perspective, applying 3D printing can enable parties to gain a competitive advantage by extending the scope of production. In this regard, production activity is no longer restricted to mass producers, who can take advantage of economies of scale. Another prominent disruption with the adoption of 3D printing is that individuals can engage to a significant extent in production activities because the threshold of market entry is reduced by 3D printing. Also, disruption is observed as digital modelling activities become more important than ever. In short, by decentralising production activities, 3D printing is significantly different from traditional mass production. Various business models are adopted to capture the value created by 3D printing. A critical task of this chapter is to categorise different business models and to explain how these business models could result in product risks differently. In general, two kinds of business models are firstly distinguished. One is called the "*one-stop*" business model, in which an entity is responsible for the whole process of production. If 3D printing is adopted in this way, it shows little difference from traditional manufacturing. The other type of business model is called the "*separation*" business model. Under this model, consumers coordinate the process of production, in which digital modelling and physical fabrication are completed by the parties from different entities. To a large extent, it is the separation model that significantly distinguishes 3D printing from traditional mass production. As the discussion in Chapter 3 further shows, dealing with product risk under the separation model could be an even more complicated issue, since the process of acquiring the CAD file and accessing the printing service are largely different in practice. This complexity has a significant impact on the procedure adopted for deterrence and risk-shifting.

Part II. Deterrence and risk-shifting in the context of 3D printing through the lens of contractual relations

Part II attempts to answer the research questions by exploring whether a contractual relationship can efficiently allocate the risks in a way that offers relevant parties with an optimal incentive and shifts the risk if necessary. This part contains two chapters.

Chapter 4 firstly explains that in an ideal world and based on several key assumptions, a socially optimal outcome can be achieved through bargaining. It goes on to explain that this socially optimal outcome cannot be accomplished provided that there are prohibitive transaction costs and ubiquitous information problems.

Chapters 5 examines the extent to which transaction cost and information asymmetry prevent parties from efficiently contracting over product risk under separation models in the context of 3D printing.

Part III. Deterrence and risk-shifting in the context of 3D printing through the lens of tort liability

Part III, which consists of three chapters, sets out to answer the research questions by addressing another mechanism: tort liability.

This part starts with a positive analysis in Chapter 6, asking whether the risks that are generated with the adoption of 3D printing are subject to extra-contractual liabilities. The chapter shows that the answer to this question is largely divergent across the Member States since they have different attitudes toward the form of the liability applied to the creator of digital goods and the service provider. One of the key findings in this chapter is that as digital goods and services are significantly affecting the performance of the final product, Member States tend to expand the application of strict liability.

Chapter 7 provides an approach based on law and economics analysis to explore the efficiency of liability rules in the context of 3D printing. The main interest is to examine whether the justifications of strict product liability still hold when production is organised under "separation models". In addition, the extent to which court errors could distort the deterrence effect is also examined in this chapter.

Chapter 8 explores the efficiency of liability rules through the lens of the risk-spreading issue. Traditionally, one point that favours strict liability is that risk can be spread over consumers through market price. However, where both consumers and producers have access to insurance to spread risk, risk-shifting might become an issue against applying strict liability. This chapter explores the extent to which uninsurability issues arise in the context of 3D printing. Further to that, if liability insurance is offered, whether problems of adverse selection and moral hazard present to distort the effect on deterrence and risk-spreading will be examined.

Part IV. Deterrence and risk-shifting in the context of 3D printing through the lens of regulatory regime and platform governance

The discussions in Part II and Part III indicate the extent to which contractual relationships and tort liability can incentivise relevant parties to behave appropriately and the extent to which such mechanisms fail to achieve a socially optimal outcome. Part IV proposes additional instruments that can potentially improve the effect on deterrence and risk-spreading in the context of 3D printing.

Chapter 9 firstly explores the role of regulations. Specifically, this chapter proposes how different regulatory methods could be used to incentivise CAD file makers and fabricators to take precautionary measures. What is more, information regulations providing additional guidance to contractual parties are expected to help consumers better understand the risk of a product and improve their decision-making.

Chapter 10 focuses on the role of online platforms. The function of the platform is analysed in two aspects. On the one hand, this chapter reveals that a platform through its governance may induce users to behave appropriately. On the other hand, a platform serving as a suitable party to observe the behaviour of insured parties can help reduce adverse selection and moral hazard problems.

PART I

THE DISRUPTION OF 3D PRINTING: A TECHNOLOGICAL AND SOCIAL PERSPECTIVE

Introduction

Before we look in-depth at the performance of various instruments in terms of achieving the goal of deterrence and compensation with 3D printing, it is necessary to develop a thorough understanding of the extent to which 3D printing as a disruptive technology externalises product risk, and to determine why these risks look so different compared to the risks generated by traditional mass production. The first part of the research will unravel some of the mysteries of the technological and social disruptions that stem from 3D printing. The discussion in this part proceeds as follows. Chapter 1 explains how 3D printing is technically differentiated from traditional mass production. Chapter 2 assesses the social factors that facilitate the development and application of 3D printing in the sector of production. Lastly, through the lens of the value chain, Chapter 3 shows that product risk is generated wherever value is added by 3D printing and, specifically, it analyses the extent to which product risk is posed under different business models.

Chapter 1. 3D Printing as a Disruptive Technology

This first chapter introduces how 3D printing works. From the technical perspective, 3D printing is composed of two separate processes: digital designing and physical fabrication. Having an overview of the technical disruptions of 3D printing helps people to understand the social transformations caused by 3D printing.

1.1. 3D printing: A conceptual and evolutionary perspective

3D printing is commonly regarded as a colloquial term for additive manufacturing (AM).[9] While AM is the standard term in industry and is also defined by relevant standard organisations such as ISO and ASTM, 3D printing turns out to be a term that has greater exposure in social media.[10] In general, 3D printing refers to an AM process, through which a physical object is produced layer by layer under the instruction of a specific digital model.[11]

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[9] See Lipson, Hod, and Melba Kurman. *Fabricated: The new world of 3D printing.* John Wiley & Sons, 2013. Weller, Christian, Robin Kleer, and Frank T. Piller. *"Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited."* International Journal of Production Economics 164 (2015): 43-56. See also World Intellectual Property Organization (WIPO), *"World Intellectual Property Report: Breakthrough Innovation and Economic Growth"* (2015); stating that "3D printing -known in the industry as additive manufacturing- refers to a set of manufacturing technologies where 3D objects are created by adding successive layers of material on top of one another, aided by specialized computer programs for both process control and object design." However, literature also indicates the slight difference between 3D printing and additive manufacturing in terminology. To clarify this diversion, the term of 3D printing is confined as an additive manufacturing that applies material extrusion method, while the term of additive manufacturing refers to all process that makes parts layer by layer. See ISO/ASTM 52900, *"Additive manufacturing: General principles and Terminology*." 2015. In this research, 3D printing and additive manufacturing are not distinguished.

[10] By 6th May 2019, the term AM produced 58 million results when a person searched it under Google. In comparison, 762 million results were shown at the same time under the term of 3D printing.

[11] Gibson, I., D. Rosen, and B. Stucker. ADDITIVE MANUFACTURING: 3D PRINTING, RAPID PROTOTYPING, AND DRICT MANUFACTURING. (2015), Springer, at 2. This definition is also recognized and widely adopted around the world. Standards promulgated by the International Organization for Standardization (ISO) and the American Section of the International Association for Testing Materials (ASTM) all adopt this definition. For example, ASTM International

From a technical perspective, two characteristics make 3D printing stand out from traditional manufacturing. Firstly, obtaining a digital model serves as an indispensable step prior to printing the object physically.[12] Secondly, 3D printing adopts an additive printing method rather than a formative or subtractive one.[13]

Despite its distinctive technical features, 3D printing only became a disruptive technology as its added value and disruptive effect on the supply chain were gradually recognised. In fact, the initial goal of 3D printing was simply to achieve rapid prototyping.[14] In 1984, the first-ever 3D printing technology was invented and patented by Charles Hull.[15] At the outset, a rudiment of modern 3D printing technology, which was called stereolithography[16], successfully transferred a digital model into a physical object.[17] This invention was a breakthrough for manufacturers at the time since they were able to prototype their products in a fast and costless way before they made the decision whether or not particular projects were worth pursuing.[18]

The complete 3D printing lifecycle consists of two major processes: the digital design process and the subsequent physical fabrication process. Prior to the emergence of 3D printing, while both of the two processes had already existed for a long time, they belonged to two domains that had few interactions.[19] The emergence of 3D printing made it possible for the building of a physical product

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defines 3D printing as "the process of joining materials to make objects from 3D Model Data, usually layer upon layer."

[12] See Campbell, Thomas, et al. "*Could 3D printing change the world*." Technologies, Potential, and Implications of Additive Manufacturing, Atlantic Council, Washington, DC (2011): 3.

[13] A complete procedure of fabrication under the traditional method typically consists of several complex processes, including casting, forming, molding and machining. See Campbell et al. (2011), supra note 12; Redwood, Ben, Filemon Schoffer and Brian Garret, THE 3D PRINTING HANDBOOK: TECHNOLOGIES, DESIGN AND APPLICATIONS. 3D HUBS, 2017, at 7-9.

[14] Holmström, Jan, and Jouni Partanen. "*Digital manufacturing-driven transformations of service supply chains for complex products*." Supply Chain Management: An International Journal 19, no. 4 (2014): 421-430.

[15] 3D Systems Corp., "*Our Story*", at https://www.3dsystems.com/our-story.

[16] Stereolithography is the so-called "SLA". By using stereolithography, a product is formed by using the laser to harden specific parts of liquid layer by layer. The working process of this technology, together with other ensuing technologies, is summarized in Table 1.1.

[17] Redshift by Autodesk, *"History of 3D Printing: It's Older than You Are"*, (2018).at https://www.autodesk.com/redshift/history-of-3d-printing/. Visited on October 5th, 2018.

[18] See Weller et al. (2015), supra note 9.

[19] While physical fabricating had evolved since the origin of human beings, designing a product in digital methods was just started in the 1960s, when computer technologies developed to make it possible. Before the emergence of 3D

from a digital design.[20] In this sense, by enabling these two bundles of technology to connect to each other, whenever a digital design is accomplished, a physical object can be anticipated.[21]

The next two subsections are organised to respectively demonstrate how the two distinctive processes perform from a *technical* perspective.

1.2. The digital designing process of 3D printing

The digital designing process is a holistic process of producing a printable digital file. Two stages are indispensable within the digital designing process. The first is the digital modelling process, in which an individual has to transform the idea of a product into a visible digital model on the screen. This digital modelling process is followed by a necessary conversion, through which the model could be saved in the digital format that can be read by 3D printers.

1.2.1. Obtaining a visible digital design

Two approaches are employed in order to produce a visible digital design.[22]

Firstly, a wide range of computer-aided-design software (i.e., the CAD software) is offered in support of this process.[23] Such CAD software is differentiated by its various levels of competence. People with a professional software engineering background can digitally model complex designs with the help of advanced software, while ordinary people who have little knowledge can also engage in the process of digital modelling by using elementary software.[24] Compared with the

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printing, even though digital designing and physical fabricating have been much advanced to a large extent, they are still two separate processes. In this sense, digital design with the proxies of a product cannot be directly produced into a physical product in a one-stop process.

[20] Mohr, Sebastian, and Omera Khan. "*3D printing and its disruptive impacts on supply chains of the future*." Technology Innovation Management Review 5, no. 11 (2015): 20.

[21] See Berman, Barry. "*3-D printing: The new industrial revolution*." Business horizons 55, no. 2 (2012): 155-162.

[22] See Gibson et al. (2015), *supra* note 11, at p.44.

[23] CAD software are easily accessible at the moment. Besides the commercial CAD software like "AutoCAD", there are also a variety of CAD software like "123D" that are open-sourced to ordinary people.

[24] For example, "Tinkercad" is considered the elementary software for people with little knowledge of digital designing. "SketchUp" is a moderate one with more complex functions to fulfil people with higher demands.

traditional way of manufacturing, the digital modelling process under 3D printing is a promising way of dealing with complex structures. All the internal parts of a product, which can barely be seen in traditional manufacturing, are now visualised for the designer.[25]

Secondly, a digital design can also be created by scanning an existing object.[26] This approach is a kind of reverse engineering, and it enables people to record digitally the proxies of various physical objects for different purposes. By processing the proxies and data in a relatively automated way, acquiring a digital design via scanning needs far less human intervention than the first method.

1.2.2. Obtaining a printable CAD file

The visible digital design gained at the stage of digital modelling is not a version that can be read and printed by the 3D printer. In order to transform the digital model into a real object, an individual has to take an extra step to export the digital model as a format that can be executed by 3D printers. The result of this computer-readable digital format is called the computer-aided design file (i.e., the so-called "CAD file").[27] Technically, the CAD file is a generic term that contains all executable digital files with different file extensions. In most cases, CAD files are saved with an extension ".stl".[28] Unlike the visible digital design, a CAD file stores the printing data in the format of surface geometry. Specifically, through tessellation technology, smaller triangles can be tiled to form the whole surface. In this way, the surface geometry of the final object is encoded into the CAD file.[29]

"AutoCAD" is a professional digital designing software, which can meet not only requirements of prosumers but also SMEs.

[25] Esmaeilian, Behzad, Sara Behdad, and Ben Wang. "The evolution and future of manufacturing: A review." Journal of Manufacturing Systems 39 (2016): 79-100.

[26] Chan, Hing Kai, James Griffin, Jia Lim, Fangli Zeng, and Anthony SF Chiu. "The impact of 3D Printing Technology on the supply chain: Manufacturing and legal perspectives." International Journal of Production Economics 205 (2018): 156-162.

[27] See Gibson et al. (2015), supra note 11, at 4-7.

[28] Other common CAD file extensions are ".dwg", ".dxf" and ".dgn".

[29] For a comprehensive understanding of the way that a CAD file stores the printable information, see https://all3dp.com/what-is-stl-file-format-extension-3d-printing/ Visited on 9th September 2018.

It should be noted that transposing a visible digital model to a 3D-printer-readable CAD file does not generate extra workload or increase the complexity of the printing process. In fact, from a technical perspective, it is easy to export the design in a format that can be read by a 3D printer as the step is embedded at the end of the digital design process.[30] The importance of the CAD file is that it enables the connection between software and hardware. In this respect, the CAD file plays a crucial role in 3D printing.[31] Since the CAD file is the ultimate output of the digital design process, it is the last chance for an individual to change the substantive content of a final object. Once a CAD file is brought to a 3D printer, apart from materials and dimensions, nothing can be changed.

In summary, the complete process of digital making witnesses a translation of a design from a visual language to a technical language that can be further read by the 3D printer. This clarification of the digital design process has significant implications for the safety of the final object. In an era when the digital world and the physical world were not connected with each other, a design would not directly result in any harm. However, since the CAD file serving as the blueprint of the object determines the function of the ultimate printed object in 3D printing, any defects will certainly result in an unsuitable object. In this sense, the technical feature of the CAD file implies that the design process plays an increasingly important role in the determination of the final product. The process of obtaining a CAD file thus is also called the process of digital making in this research.

1.3. The physical fabrication process

Following on from the digital designing process, the purpose of the physical fabrication process is to print the CAD file as a real object. In general, a complete physical fabrication process is divided into three phases: pre-printing, printing and post-printing.[32]

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[30] See Gibson et al. (2015), supra note 11, at 4.

[31] See Berman (2012), supra note 21.

[32] In some literature, different terms are used to dictate the same processes under a holistic physical fabricating process. For example, a pre-printing process is equivalent to "machine setup"; printing process is also called "building". See Gibson et al., *supra* note 11, at 47-49.

1.3.1. The pre-printing phase

The CAD file represents the terminal language of a digital design process. Although it serves as a signal that a printable CAD file is finished, it is not a guarantee that the CAD file can be printed out by a native 3D printer. Digital making and physical fabrication are respectively fron software and hardware systems. While the CAD file records all of the geometric information about the object, the method for identifying such information and arranging the steps of printing is still proprietary to different 3D printers.

In practice, a special process called the *slicing process* is necessary prior to printing.[33] With the help of the slicing program, the location of the supporting parts, the dimensions of the object, and the colours and materials to be used will be specified. The outcome of this slicing process is the so-called *G-code file*. As a numerical controlling programming language, the G-code file serves as an instruction to guide the printing process of a specific local 3D printer.

Therefore, the leap from a CAD file to a G-code file represents a connection between the software system and the hardware system. However, it should be clarified that it is the CAD file rather than the G-code file that determines the final product. In comparison, the G-code file only determines the printer settings, and it does not alter the functions of the final product. Moreover, the CAD file is the medium that is presented on various online platforms, which can be downloaded and modified by individuals, while the G-code file is only accessed in the native printing context.

1.3.2. The fabricating (printing) phase

The printing process, which takes place after the system of the 3D printer has identified the CAD file, serves as the core procedure in whole physical farbciation. By the end of a printing process, a physical product is produced by the 3D printer.

[33] Different slicing programs are installed in different 3D printers, and these programs acquire the geometric data that is stored within a CAD file and slice it into tens of thousands of layers. At the current stage, more and more open-source slicing programs are developed, and they are compatible with different kinds of 3D printers. For example, an open-source slicing programming called "Cura" is developed by Ultimaker, who installs it onto the 3D printers made by it. See Wohlers Associates, Inc., Wohlers Report 2015, at 116.

The printing process can be classified into seven different categories according to the state of the art.[34] They are:

- Vat photopolymerisation
- Powder bed fusion
- Material extrusion
- Material jetting
- Binder jetting
- Direct energy deposition
- Sheet lamination

This classification is provided by the ISO/ASTM 52900 standard.[35] Under each category, there are one or more subcategories.[36] The definition of each printing process is summarised in Table 1.

The properties of the different fabrication processes have a further substantial impact on the scope of applications. The decision as to which fabrication process to adopt is initially taken from the technical perspective, which means that stakeholders are always willing at the beginning to adopt the most competitive fabrication process. However, their final decision may be different from their initial idea, since factors other than technical considerations constrain their choice. For example, provided that someone can invest a little money to engage in 3D-printing-related activities, then a fabrication process such as material extrusion or vat photopolymerisation may be the first choice since relevant 3D printers are not expensive and the materials are readily accessible. In contrast, if

[34] See Redwood et al. (2017), supra note 13, at 20-21. See also Gardan, Julien. "Additive manufacturing technologies: state of the art and trends." International Journal of Production Research 54, no. 10 (2016): 3118-3132.

[35] For the details, see: https://www.iso.org/standard/69669.html. Visited on 11th September 2018.

[36] Vat photopolymerization can be further categorized as stereolithography (SLA), digital light processing (DLP) and continuous digital light processing (CDLP) according to the different sources of light. Similarly, powder bed fusion can be classified as selective laser sintering (SLS), Selective laser melting and direct metal laser sintering (SLM & DMLS), electron beam melting (EBM) and multi-jet fusion (MJF). Material extrusion only refers to fused deposition modeling (FDM). Material jetting includes material jetting (MJ), nanoparticle jetting (NPJ) and Drop on Demand (DOD). Binder jetting currently has no subcategories. Direct energy deposition includes laser engineering net shape (LENS) and electron beam additive manufacturing (EBAM). At last, sheet lamination has two subcategories at the current stage: laminated object manufacturing (LOM) and ultrasonic additive manufacturing (UAM).

someone attempts to provide qualified metal car components and they are wealthy, then a method such as powder bed fusion or direct energy deposition may be the preferred choice.

Table 1: Categories of 3D Printing Technology[37]

	Vat photopolymerisation	Powder Bed Fusion	Material Extrusion	Material Jetting	Binder Jetting	Direct Energy Deposition	Sheet Lamination
Subcategories	SLA DLP CDLP	SLS SLM/DMLS EBM	FDM	MJ NPJ DOD	BJ	LENS EBAM	LOM UAM
Working Rational	Light-sensitive photopolymer resins are solidified when they are exposed to light. The building platform, which is initially placed just one layer lower than the resin surface, keeps moving downward whenever one layer is finished. One should take the object out of the vat of resin when the printing process is completed.	Thermal-sensitive powders are solidified when they are exposed to thermal sources. The building platform, which is initially placed just one layer lower than the powder surface, keeps moving downward whenever one layer is finished. The object is encapsulated in the vat of powders.	Thermoplastic materials in filament form are melted and extruded from a nozzle. The extruded materials are kept laying down on the platform.	Materials are extruded from hundreds of nozzles to build a layer at one time. The extruded materials are hardened when they are exposed to the Ultraviolet light environment.	Powders that have been placed into the bed would bind with each, whenever binding droplets are deposited onto them. Whenever a layer is completed, a new layer of powders will be spread onto it until the printing process is accomplished.	Powders are sprayed from nozzles. A laser or electron beam is then used to create a melt pool, where the deposited powders are melted and then solidified.	Sheets or ribbons of materials are bonded together by ultrasonic welding.
Materials	plastic, polymers	plastic, nylon, polyether ether ketone (PEEK), Metal (Titanium, Aluminium, stainless steel, nickel alloys, cobalt-chrome)	plastic (PLA, ABS, PEI, TPU)	stainless steel, ceramics, wax	stainless steel, ceramics, cobalt-chrome, tungsten-carbide, silica sand, gypsum, polymers (ABS, PA, PC)	titanium, stainless steel, aluminium, copper	Paper, plastic, some sheet metals (Aluminium, copper, stainless steel and titanium)
Endurance and Quality	low endurance (not for mechanical purpose)	solid (suitable for mechanical purpose)	low endurance (not for mechanical purpose)	low endurance (not for mechanical purpose)	medium endurance (poorer mechanical properties than SLM)	solid endurance and high quality	relying on the adhesive
Applications	suitable for parts with high requirement of surface (jewellery, dental)	suitable for fine arts and functional parts (aerospace, automotive, medical)	suitable for rapid prototyping and production	suitable for realistic prototyping and production	suitable for fine arts	suitable for repairing components	

[37] The contents of this table are summarized from two sources. See Redwood et al., supra note 16. See also Additive Manufacturing Research Group of Loughborough University, "The 7 Categories of Additive Manufacturing", see at http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/

1.3.3. The post-printing phase

The body of the object is physically structured after a successful printing process. However, the printed object may not be put into use directly until necessary post-printing activities are completed.[38]

For a specific printing process that adopts a method like material extrusion or material jetting, *supporting structures* are necessary in order to support the suspended part of the object. Once the printing process has been accomplished, these supports are manually removed from the main bodies.[39] In addition, to create an object with a smooth surface, additional processes such as sanding and polishing are required to remove marks from the surface.

Along with producing an excellent surface finish, post-printing processes are also necessary when the object is intended for a demanding purpose. For example, a metal-coating may be applied to enhance conductivity or water-tightness might be required.

To conclude, an automated printing process is usually followed by a post-printing phase, in which fabricators play a dominant role in improving the usability of the printed object.

1.4. Chapter conclusion

This chapter introduced the whole process of 3D printing from a technical perspective. As shown in Figure 1, a specific 3D printing process is composed of the process of digital designing and physical fabrication.

[38] Griffin, Matt. "Skill Builder — Finishing and Post-Processing Your 3D Printed Objects", available at: https://makezine.com/projects/make-34/skill-builder-finishing-and-post-processing-your-3d-printed-objects/. Visited on June 6th, 2017.

[39] Basically, there are two ways to remove such supporting structures. One is called standard support removal, in which individuals could use needle-nose pliers to remove support materials. The other is called dissolvable support removal, in which the printed object is placed into the container where solvents are already put.

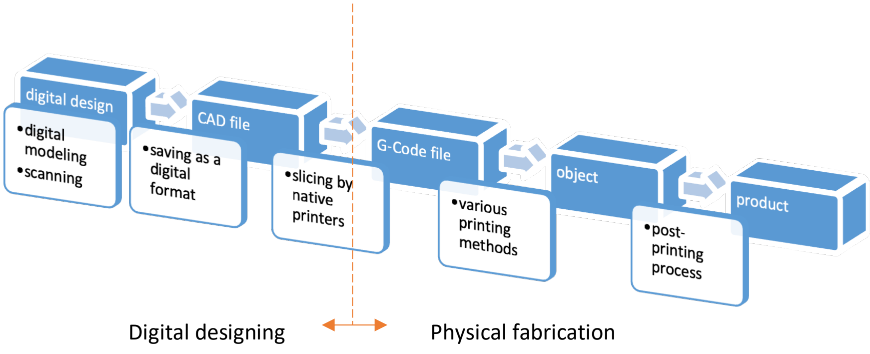

Figure 1: The complete process of 3D printing

Some interesting points can be concluded from the technical perspective.

Firstly, a complete process of 3D printing is divided into two a digital designing process and a physical fabrication process. This separation indicates that in practice the complete production could be accomplished either by different departments that from a signal party or by different parties who are strangers to each other.[40] Secondly, the digital design process seems to be more important than the subsequent physical fabricating one, since the primary function and performance of the final product is mainly contingent on the former process.[41] Thirdly, the increase in the importance of digital design activities does not necessarily mean that the quality of a final product is irrelevant in the fabrication process. Fabricators can still play a critical role by determining the choices of elements such as material and size.[42] Their influence is not mainly reflected in determining the function of the product, but on the associated performance and properties of the product. The technical disruptions promised by the application of 3D printing

[40] See the analysis under Section 1.2.1 and Section 1.3.2.

[41] See the analysis under Section 1.2.

[42] See the analysis under Section 1.3.1.

cannot be achieved without the support of other social factors. In the next chapter, we explore the extent to which various social factors are driving 3D printing, turning it from a typical hyped technology to something that makes a substantial contribution to the production sector.

Chapter 2. The Development of 3D Printing: Transiting from Labs to Commercialisation

The potential disruptions brought about by 3D printing are not only driven by technical advances but also by the rapid growth in its application. In practice, the competition regarding 3D printing technologies could be observed through the lens of intellectual property (IP). In addition, having realised the importance of 3D printing in developing domestic market, countries around the world are issuing policies pro the development of 3D printing. This chapter will have an overview of the stimulus of 3D printing. In the last section of this Chapter, some industries that are mostly disrupted by 3D printing would be introduced. The description in this chapter indicates that 3D printing could create value in a wide range of areas, which in turn poses risk to the society as well.

2.1. Commercialisation through the lens of IP

2.1.1. Patent as a safeguard in the early stage of commercialisation

An important prerequisite for the commercialisation of any kind of technology is the patenting of its essential inventions and methods.[43] Patenting grants an enterprise exclusive right for 20 years.[44]

In 1984, the first 3D printing method (i.e., stereolithography) was invented, and Charles Hull filed a patent for the apparatus. Two years later, in 1986, this patent was approved by the US Patent and Trademark Office (USPTO), and this heralded the start of commercialisation of 3D printing. Holding this key patent, *3D Systems* was founded in 1986 as the first company that focused on 3D

[43] Kitch, Edmund W. "*The nature and function of the patent system*." The Journal of Law and Economics 20, no. 2 (1977): 265-290.

[44] According to Article 33 of TRIPs, the term of patent protection should be no shorter than 20 years from the filing date of the application.

printing technology. The company subsequently filed other patents on the technology and printing methods.[45]

The success of *3D Systems* is just a miniature version of the commercialisation of the 3D printing industry as a whole. Since the 1990s, numerous start-ups have repeated this roadmap by commercialising new 3D printing technologies. Table 2 summarises the patents of specific methods and apparatus related to 3D printing. It is evident that enterprises played an essential role in the promotion of 3D printing at the early stage, and most of the patents were issued in the US.

Table 2: The Patent Landscape of 3D Printing

Technology	Type	Issued Year	Applicant	Patent Number
SLA	apparatus	1986	Charles W. Hull (3D Systems Inc)	US4575330A
SLS	apparatus and method	1989	Carl R. Deckard (University of Texas)	US4863538A
SLA	method	1990	Charles W. Hull (3D Systems Inc)	US4929402A
FDM	apparatus and method	1992	S. Scott Crump (Stratasys Inc)	US5121329A
LOM	apparatus and method	1998	Michael Feygin et al. (Helisys Corp)	US5730817A
LENS	method and system	2000	Francisco P. Jeantette et al. (Sandia Corp)	US6046426A
DLP	apparatus and method	2002	Lawrence E. Brown (Rolls-Royce Corp & University of Texas)	US6355086B2

[45] To date, 3D Systems has been one of the top patent applicants in the world. Since 1995, 200 first patent filing has been applied by 3D System. See WIPO (2015), *supra* note 9, at 101.

2.1.2. The current state of patents and 3D printing

Despite the commercialisation of the apparatus and methods of 3D printing mentioned above, the potential of 3D printing was not unleashed as had been expected during the 1990s and 2000s. An important reason lies in the existence of patents. In this sense, the function of a patent is twofold. Firstly, it awards exclusive rights to the first entrant to the relevant market. Secondly, it punishes and deters those followers who fail to be the first and who intend to engage in similar activities around the essential inventions. During the 1990s and 2000s, the fundamental apparatus and methods were barely accessible because they were under the control of only a few patentees. Whenever manufacturers in specific industries intended to adopt 3D printing, they had to obtain licences at a high cost.

This situation has improved as several essential patents have expired in recent years. More start-ups, as well as other entities, are able to access core technologies, and further innovations and patent applications are thus stimulated. Figure 2 shows the increase in the number of patents applied for and issued.[46] It can be seen that the volume increased significantly after 2006, which is roughly 20 years from when the first patent for 3D printing was issued.

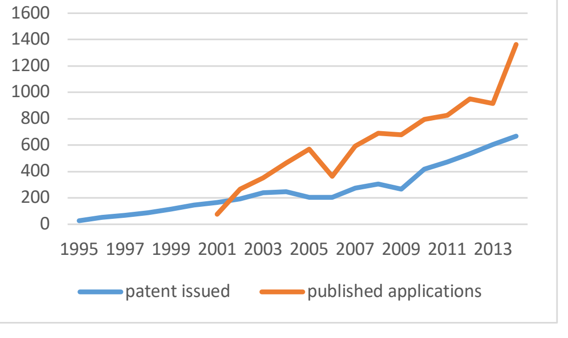

Figure 2: The number of issued patents and published applications (1995-2014)[47]

[46] Wohlers Report (2015), supra note 33, at 213.

[47] Data source: Castle Island.

If we look at the trends in the commercialisation of 3D printing through the lens of patents, some exciting findings can be further identified. Firstly, the market for 3D printing is still dominated by SMEs.[48] This is consistent with our expectations from the technical features of 3D printing, since it lowers the threshold of the industry and SMEs are able to find a competitive advantage.[49] Secondly, the system providers (i.e., the fabricating methods developers) are led by two large companies (i.e., *Stratasys* and *3D systems*). This evidence is also consistent with Section 2.1.1, which showed that the "scale", though having been largely removed, still exists in the field of the fabrication process.[50] With a competent R&D capacity, large companies are expected to gain a more competitive place. Thirdly, the sources of the patents are extensive. While enterprises still account for most patents, universities, as well as research institutions, turn out to have non-negligible power.[51]

2.1.3. Commercialisation via the capital market

The potential of the 3D printing market is also recognised by venture capital. By October 2019, 619 rounds of funding had been completed, and a total of $2.5 billion had been invested in 3D printing start-ups in support of their activities.[52] The support of the capital market has enabled the growth of many start-ups in recent years.

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[48] According to the description of the WIPO, "The industrial 3D printing market is mainly comprised of small and medium enterprises". See WIPO (2015), supra note 9, at 101.

[49] Rayna, Thierry, and Ludmila Striukova. "*From rapid prototyping to home fabrication: How 3D printing is changing business model innovation.*" Technological Forecasting and Social Change 102 (2016): 214-224.

[50] According to the data from the WIPO, the top two firms that filed patents for 3D printing between 1995 and 2015 are 3D Systems and Stratasys, which are professional entities focusing on 3D printing technologies. These two large companies, together with other traditional manufacturers (e.g. Simmens and General Electric), dominate the landscape of patent filing in the past two decades. See WIPO (2015), supra note 9, at 101.

[51] WIPO (2015), supra note 9, at 102.

[52] For detailed information, see: https://www.crunchbase.com/hub/3d-printing startups/recent/org_recent_funding_rounds_list#section-recent-activities. Visited on 7th October 2019.

Founded in 2013, the US-based enterprise *Carbon* benefited greatly from fundraising. *Carbon*, as the pioneer that developed so-called Digital Light Synthesis technology, offers customised solutions. This technology is provided to many businesses that are in need of customised product solutions, such as GE, Adidas and BMW and which are, in return, willing to support the development of *Carbon*. By October 2019, *Carbon* had successfully completed six rounds of funding and had raised a total of $682 million.[53] With support from the capital market, *Carbon* can put more money into its R&D activities. To date, *Carbon* has developed ten material families and eight types of biocompatible resins. In addition, 35 patents have been issued to *Carbon*, and more than 250 are currently pending.[54] The development of *Carbon* is an example of how 3D printing start-ups can gain a competitive advantage with the help of the capital market.

This success can also be found in other regions and in the companies adopting different business models. On the other side of the Atlantic, *3D Hubs*, a platform for connecting customised demand and supply, also shows great potential. Founded in 2013, *3D Hubs* has already raised four rounds of funding with $29.5 million.[55] Investment from the capital market offers the chance to expand the size of a company and transform its business model to capture value from 3D printing.[56]

2.2. National strategies to support the development of 3D printing

Developing 3D printing not only relies on the bottom-up efforts of R&D and commercialisation by the private sector but also depends on top-down supports from national authorities. In recent years, as different countries have come to appreciate the potential of 3D printing to boost economic prosperity, strategies and measures have been taken in support of the development of 3D printing.

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[53] For the details of the funding raised by Carbon, see: https://www.crunchbase.com/organization/carbon3d. Visited on October 7th, 2019.

[54] Such information is obtained from the official website of Carbon. See: https://www.carbon3d.com/5thanniversary/. Visited on September 22nd, 2018.

[55] For the details of the funding raised by 3D Hubs, see: https://www.crunchbase.com/organization/3d-hubs. Visited on October 7th, 2019.

[56] The content on how 3D Hubs transformed its business model and the results of it will be discussed in Section 3.3.2 and 10.1.

The purpose of this section is to give a brief overview of how national authorities are making efforts to stimulate the development of domestic 3D printing sector.

2.2.1. EU: FP7 and Horizon 2020

3D printing is treated as one of the Key Enabling Technologies (KET) in the EU. Its importance to the industrial future of Europe is reflected in a couple of essential EU strategies.[57] Along with other technologies, including IoT, big data, artificial intelligence and robotics, 3D printing is considered an important element in driving digital change and "respond[ing] to major aspirations of today's customers".[58] Also, 3D printing is recognised as a critical driver of growth in the job market, incentivising people to start their own business.[59] Therefore, promoting research into 3D printing and the development of businesses is consistent with the core values of the EU.

While the landscape of 3D printing across the EU is promising, it is also challenging. There is a substantial divergence in different regions in terms of the capacity to develop 3D printing. Western European countries like Germany, the UK, the Netherlands, Belgium and France are leading 3D printing around the world. In sharp contrast, Eastern European countries have fallen behind in this round of technological revolution.[60] In addition, a divergence is also evident among different application areas. 3D printing is most developed in areas like surgical planning, inert and hard implants, and metal AM for injection moulding and metallic structural parts for aircraft. It has been reported that the value chain in these sectors is well established. In comparison, in some other applications, 3D printing still lacks competence, which leads to demands for collaboration opportunities.[61]

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[57] For example, under the communication "A Stronger European Industry for Growth and Economic Recovery", 3D printing is viewed as a game-changer in terms of transforming the production of goods. See: The European Commission, A Stronger European Industry for Growth and Economic Recovery, COM(2012) 582 final, 2012.

[58] The European Commission, "Digitising European Industry Reaping the full benefits of a Digital Single Market", COM(2016) 180 final, at 4.

[59] The European Commission, "Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing): Final Report", 2016, at 29.

[60] See The European Commission (2016), supra note 59, at 18.

[61] See The European Commission (2016), supra note 59, at 16-17.

In recent years, in order to fill in the gap and to promote value creation in 3D printing, a variety of measures have been promoted by EU authorities.

Firstly, *funds* are increasingly provided in support of research on 3D printing. Table 3 shows the number of 3D printing projects that are funded by recent Framework Programmes (from FP3 to FP7). Additional value creation by key technologies mainly occurs in three areas: products, processes and business models. In order to maximise value creation in these areas, related projects are financially supported to a large extent. Around 30% of the funded projects focus on expanding the scope of materials that are used for 3D printing and 35% centre on optimising the methods and processes of 3D printing. The last 35% are application-related programmes. The importance of 3D printing is also reflected in Horizon 2020 (2014-2020), the biggest EU Research and Innovation programme, in which a total of 27 projects related to 3D printing were granted funds of more than €113 million.

Table 3: Funded 3D-printing-related projects from FP3-FP7[62]

EC Programme	The number of supported projects
FP3	4
FP4	10
FP5	4
FP6	11
FP7	64

In addition, strategies to enhance collaboration have been initiated by various EU authorities. The European Commission (EC) plans to use €500 million from Horizon 2020 to support cross-border collaboration and to mobilise regional cooperation.[63] A specific virtual innovation centre called AM Platform (i.e., the European Additive Manufacturing Technology Platform) was established to promote a coherent strategy to achieve the Lisbon and Gothenburg objectives of making the EU

[62] See The European Commission (2016), supra note 59, at 39.

[63] See The European Commission (2016), supra note 59, at 8.

become the most dynamic, knowledge-based economy by 2010 and to achieve sustainability by 2030.[64] Under this strategy, partners from industries (especially start-up SMEs), research institutions, government bodies and industry associations are linked with each other. More importantly, a public-private partnership was set up to play a critical role in promoting the development of 3D printing across the community; the so-called "Factories of the Future Public-Private Partnership (FoF-PPP)" initiative has a budget of €1.15 billion for the period 2014 to 2020. As the EC noted, the goal of this initiative is "helping EU manufacturing enterprises, in particular SMEs, to adapt to global competitive pressures by developing the necessary key enabling technologies across a broad range of sectors."[65] This FoF-PPP initiative will also help European industry "to meet increasing global consumer demand for greener, more customised and higher quality products through the necessary transition to a demand-driven industry."[66]

Standardisation is crucial in the development of 3D printing in the EU. In 2014, a roadmap on standardisation for 3D-printing was delivered. This roadmap is consistent with the strategy put forward by AM Platform, and it was drawn up by the SASAM (Support Action for Standardisation in Additive Manufacturing), a project that was funded by FP7.[67] The roadmap serves as a template for further development of European standards, and it aims to promote the acceptance of standards across the industry and facilitate industrial compliance. International cooperation of three bodies (i.e., ISO TC261, ASTM F42 and CEN/TC 438) was guaranteed within the roadmap. A consensus structure on 3D printing standardisation was reached.[68]

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[64] See https://www.rm-platform.com/. Visited on June 10th, 2017.

[65] The European Commission, Factories of Future PPP: towards competitive EU manufacturing, 2013. Available at: https://ec.europa.eu/research/press/2013/pdf/ppp/fof_factsheet.pdf. Visited on June 10th, 2017.

[66] See The European Commission (2013), supra note 65. Visited on June 10th, 2017.

[67] SASAM, Additive Manufacturing: SASAM Standardisation Roadmap, 2014. Available at: http://rm-platform.com/downloads2/send/2-articles-publications/607-sasam-standardisation-roadmap-2014. Visited on June 10th, 2017.

[68] In general, the work of standardization for 3D printing is structured into three levels: general standards, category standards and specialized standards.

2.2.2. The UK: National Strategy 2018-2025

According to the data, by the end of 2015, the UK had only captured £235 million from business related to 3D printing for the global value chain, with fewer than 5,000 associated jobs.[69] The government of the UK intends to increase these two figures to £3,500 million and 60,000 jobs by the end of 2025. To achieve this goal and to enable the UK to lead in the exploitation of the value that is created around 3D printing and to be more competitive in the global market, a national strategy on the advancement of 3D printing was issued in 2017 by AM UK, an independent government-supported collaborative body.

In its national strategy, AM UK identified several challenges that hindered further development of 3D printing in the UK. The first and foremost was a lack of funding to increase awareness and reduce the risk of adoption. In addition, skills and education were limited, which meant that the workforce was inadequate to support development. Furthermore, the national strategy suggested that current legal regimes "are not appropriate for the digital networks and ways of working required for additive manufacturing" and they prevent rapid technology adoption.[70] Standards and certification were also missing in nearly all sectors (ranging from materials to digital modelling, printing process and final products). The lack of standards resulted in the dilemma that no valid standard could be referred to in order to test the reliability of 3D printing, which was further recognised as an obstacle to expanding the application of 3D printing technologies. There was also concern about Brexit, as the UK may lose the ability to collaborate with the EU and its Member States.

Having revealed the barriers that prevent the UK from exploiting 3D printing and capturing the value created by it, recommendations were put forward in the national strategy under seven categories. Table 4 briefly summarize this national strategy.

[69] The AM UK, National Strategy 2018-2025: Leading Additive Manufacturing in the UK, 2017, at 5.

[70] The AM UK (2017), supra note 69, at 24.

Table 4: An overview of the UK's national strategy on 3D printing[71]

Value creation process	Key measures to capture value
Design	• Commissioning a study on design guidelines • Running an R&D programme to address gaps in knowledge of digital modelling • Providing support for challenge-led, strategic design activity
Material and Process	• Collation and publication of case studies of best practice • Fund R&D activity around the creation of online tools to help educate potential users • Supporting R&D and other programmes to develop equipment capability • Supporting R&D on optimising 3D printing • Increasing funding into the development of new materials
Inspection, Test and Standards	• Making standards in collaboration with industries • Developing a testing process • Developing and maintaining accessible material properties and standards database
Commercial, Intellectual Property and Data Management	• Running co-ordinated exercises to identify related IP issues • ***Implementing a 3D-printing-related product liability definition*** • Financial investments to help all sizes of entities to adopt 3D printing
Skills and Education	• Developing apprenticeships and vocational training • Building and connecting the 3D printing community • Creating and running an AM awareness campaign
Supply Chain Development	• Producing a map of the UK 3D printing supply chain capability • Extend the Catapult 'Reach' programme targeting SMEs
Implementation	• Developing links to all aspects of the digital space • Clarifying digital manufacturing-related licencing, payment methods, design and collaboration • Supporting the development of an expert UK AM User Group • Establishing and running a national help and contact point organisation

AM UK believes that acting on these recommendations will allow new opportunities to be seized and industries to prosper. Specifically, new business models are expected to be deployed, and value will be further created and captured in niche markets.[72] Also, new jobs will be created with 3D printing.

[71] This table is summarized from the National Strategy 2018-2025. See: The AM UK (2017), supra note 69, at 26-32.

[72] The AM UK (2017), supra note 69, at 42.

2.2.3. China: Made in China 2025

In China, the first national strategy on advancing the development of 3D printing was issued in 2015 (i.e., the Promotion Plan (2015-2016)).[73] Before this plan was issued, the development of 3D printing in China was generally located in research institutes. Therefore, the aim of this national strategy was to explore robust applications for 3D printing in the market. This national strategy was immediately implemented by local governments as well as relevant ministries. In 2015 and 2016, concrete plans at different levels were implemented.

According to the data from the Additive Manufacturing Association of China (AMAC 中国增材制造产业联盟), compared with 2015, the output value by large-scale enterprises in China increased by 87.5% in 2016.[74] The data also shows that most of the value is created in the hardware (50.1%) and materials (26.9%) sectors. In contrast, only 23% of the value is contributed by the application area.

In order to encourage the use of 3D printing in the application area and realise the potential of 3D printing, the Chinese government decided to take a step further by replacing the Promotion Plan with an Action Plan (2017-2020).[75] More importantly, the plan to develop 3D printing is included in the highest-level national strategy, "Made in China 2025".[76] Some areas are priorities for development. Firstly, the strategy supports the R&D of new printable materials and enlarges the investment in hardware as well as software. Secondly, it focuses on the application of 3D printing, not only at the industrial level (aerospace, shipment, automotive, etc.) but also in links with other sectors (e.g. healthcare, consumption, education and digital platforms). Thirdly, the government sees the benefit of innovation in business models and plans to build several pilot projects. Fourthly, the government realises the importance of standards and certifications and will take measures to

[73] Ministry of Industry and Information Technology, "National Additive Manufacturing Industry Development and Promotion Plan (2015-2016)", 国家增材制造产业发展推进计划 (2015-2016 年).

[74] CCID, China AM Industry Development Report ("中国增材制造产业发展报告"), 2017.

[75] Ministry of Industry and Information Technology, "National Additive Manufacturing Industry Development and Action Plan (2017-2020)", 国家增材制造产业发展行动计划（2017-2020）.

[76] The State Council of the PRC, "Made in China 2025" ("中国制造 2025), 2015. Available at: http://www.gov.cn/zhengce/content/2015-05/19/content_9784.htm

encourage collaboration among stakeholders (e.g. research institutes, enterprises and government bodies).

Having pointed out the future direction of 3D printing, an array of concrete measures is promised in the Action Plan (2017-2020) to ensure the potential can be achieved. Firstly, different officials, ranging from ministries to local governments, should intimately collaborate with each other to make sure that relevant policies can be implemented smoothly. Secondly, financial support is necessary. In this sense, a variety of financial instruments (e.g. funds, finance leases, insurance as well as capital market) should be introduced to bring more investment to areas related to 3D printing. Thirdly, international cooperation is encouraged; the government will guide and help mergers and acquisitions in the international market and will also take measures to attract foreign companies to set up R&D centres in China. Fourthly, the government has also noticed the potential risk associated with 3D printing. A specific regulatory regime is proposed in two directions: a real-name registration system to make sure that anyone who is engaged in 3D-printing-related activities (e.g. designing, manufacturing, retailing and application) can be traced, and specialised platforms to provide data surveillance.

In order to promote the implementation of the national strategy, since 2016, supporting systems have also been established in China. Firstly, specific institutes have been established to coordinate stakeholders. A national centre called the National Innovation Institute of Additive Manufacturing (NIIAM 国家增材制造创新中心), which consists of five universities and thirteen enterprises, was set up to promote commercialisation of laboratory innovations. In addition, the AMAC was set up under the Promotion Plan (2015-2016). At the time of its establishment, AMAC included 128 members, ranging from research institutes to enterprises and government bodies. Unlike NIIAM, which is a de facto enterprise, AMAC is a non-profit organisation whose role is to accelerate the development of 3D printing with the help of public-private partnership (PPP). Secondly, institutions were established at the same time to provide further support. Specific attention is paid to product quality and standardisation. The China Additive Manufacturing Product Quality Testing Center (CAMT 国家增材制造产品质量监督检验中心) is a body affiliated to the State Administration for Market Regulation (SAMR 全国增材制造标准化技术委员会).[77] By

[77] The CAMT at the moment has intensive cooperation with other institutes worldwide. It is a member of the ISO TC261.

employing experts in various areas and purchasing professional testing machines, the CAMT performs a service to assess the quality of products that are 3D-printed. In addition, the State Additive Manufacturing Standardisation Commission was established as the specific department to undertake the work of standards under Made in China 2025.

2.2.4. US: America Make

By the end of 2010, the number of people employed in the manufacturing industry in the US was 11.6 million, a significant reduction compared with the figure of 17.6 million in 1998. By 2009, the US dropped to third place after China and Germany in terms of export value. Confronted with this issue, President Barack Obama initiated a national strategy called the Advanced Manufacturing Partnership (AMP) in June 2011, the purpose of which was to secure the leading position of the US in the manufacturing industry at a time when a bundle of new technologies was emerging. To implement the national strategy, $1 billion was invested through the National Network for Manufacturing Innovation. This national network served as the first partnership to collaborate with various parties across the public as well as the private sectors to help manufacturing industry prosper. Affiliated with the AMP, an initiative called "America Makes" to focus specifically on 3D printing technology was put forward. As a PPP, the goal of America Makes is to accelerate the development of 3D printing in the US by facilitating collaboration between all stakeholders from industry, academia and government.[78]

In October 2018, a new national strategy called "Strategy for American Leadership in Advanced Manufacturing" was issued by the National Science and Technology Council. 3D printing again was seen as a pivotal technology to revitalise American manufacturing industry.[79] Within these strategies, several measures have been emphasised with specific regard to 3D printing. Firstly, from a technical viewpoint, developing world-leading materials and processing technologies

[78] The specific organization to maintain and manage the PPP is an NPO called National Center for Defense Manufacturing and Machining (NCDMM). The headquarter of the NCDMM was set up in Youngstown, Ohio.

[79] NSTC, Strategy for American Leadership in Advanced Manufacturing, 2018, at 5. Available at: https://www.whitehouse.gov/wp-content/uploads/2018/10/Advanced-Manufacturing-Strategic-Plan-2018.pdf. Visited on 21st, January 2019.

serves as the core.[80] Secondly, new standards in support of the presentation and evaluation of the data need to be established in order to ensure the quality and reproducibility of the parts that are 3D-printed.[81] Thirdly, education of the workforce on CAD file making and fabrication is of great importance.[82] Fourthly, SMEs will be continuously supported in the PPP. To explain, SMEs are considered to play a significant role in terms of innovating and adopting new business models.[83] As a consequence, giving support to SMEs will promote the development of 3D printing in the application sector.

2.2.5. Asia-Pacific region

Having realised the potential of 3D printing in revitalising domestic manufacturing industry, other countries have also developed national strategies in support of the development of 3D printing. One of the most promising areas is the Asia-Pacific region.

In 2014, a roadmap for 3D printing strategic technology was released by the MOTIE (Ministry of Trade, Industry and Energy) of South Korea.[84] This national strategy delineates ten areas that should be promoted by the government in the context of 3D printing. Following the roadmap, a specific revitalisation plan was issued in 2017, which listed the specific measures that will be employed to promote 3D printing. Firstly, the government set out to support the growth of enterprises in the sector of facilities, materials and software to make sure that several companies could be worldwide leaders by the end of 2019, which would make South Korea one of the leading countries in the market of 3D printing. Secondly, the roadmap paid attention to increasing the

[80] See NSTC (2018), id., at 11.

[81] See NSTC (2018), id., at 12.

[82] See NSTC (2018), id., at 19.

[83] See NSTC (2018), id., at 25.

[84] For the detailed information, see: http://english.motie.go.kr/en/pc/pressreleases/bbs/bbsView.do?bbs_cd_n=2&bbs_seq_n=305. Visited on August 8th, 2017.

reliability of products and to setting out standards applicable to the 3D printing industry.[85] Thirdly, the government aimed to increase support to SMEs in the following years.[86]

Singapore issued its National Additive Manufacturing Innovation Cluster (NAMIC) in October 2015.[87] The main task of NAMIC can be explained in five aspects. Firstly, NAMIC serves as an organisation to foster collaboration in the 3D printing industry. Secondly, NAMIC offers help in innovating business models. Thirdly, NAMIC operates as a platform for testing and implementing 3D printing technologies. Fourthly, NAMIC provides training and certification in the realm of 3D printing. Lastly, NAMIC accelerates the application of 3D printing.

2.2.6. Summary

This subsection outlines the global landscape related to fostering 3D printing development with the stimulus of national strategies; a number of similarities are shared between countries.

Firstly, developing 3D printing as a national strategy is directed by governments, but they rely on the *market* to achieve many goals. Several specific features are apparent in this pattern. An independent body affiliated to the government is commonly observed across the world.[88] It serves as an organisation to consolidate the collaboration among different stakeholders, ranging from enterprises to research institutes and government bodies. In addition, massive public funds are provided in support of many projects, including research on fundamental issues and the exploration of business models.

Secondly, a balance between promoting 3D printing and safety is observed in nearly all of the national strategies described above. In this sense, all the countries recognise safety as a critical factor in promoting the development of 3D printing rather than an investment that can be omitted.

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[85] Various measures are adopted in order to achieve this goal. For example, all the service and product providers should provide sufficient information regarding to their service and production to the downstream parties. Also, the government intends to lead the work on standardization in the context of 3D printing.

[86] Concrete measures in support of SMEs are: (1) setting-up a one-stop post-service center for all SMEs, which thereby helping them to capture the value at the end of supply chain; (2) employing various instruments to increase the ability of them in terms of resisting the risks; (3) Offering consulting service to them with respect to intellectual property, product reliability, export as well as technical development; (4) offering tax preferences to the supported enterprises.

[87] The official website of national strategy can be found at: https://namic.sg/about-us/. Visited on August 8th, 2017.

[88] Typical examples are the AM UK in the UK, the AMAC in China, and the NCDMM in the US.

In order to reduce risks in the process of developing 3D printing, two directions are stressed explicitly in the national strategies: all the national strategies see standardisation as vital, and there is a consensus on the need to offer safe products for sale. For this latter point, a variety of instruments, ranging from liability regimes to regulatory regimes, are proposed by countries. However, no consensus has been reached on the question of which instrument is efficient or could be more effective than the others.

Thirdly, from the application perspective, two factors are valued as drivers of the development of 3D printing. Firstly, SMEs are considered essential in the exploration of the application of 3D printing. An environment that caters for SMEs is thereby desirable. Secondly, in order to ensure that 3D printing products and services can be meet in the demands of the market, innovations on business models are encouraged.

2.3. Practical applications in different sectors: case studies

With consistent technical advances as well as booming commercialisation, 3D printing is playing an increasingly important role in the sector of production.[89] This subsection centres on emerging applications of 3D printing. Specific cases are introduced to show the extent to which 3D printing is transforming product solutions.

2.3.1. Rapid manufacturing

One of the primary applications of 3D printing remains in its traditional function of rapid manufacturing.[90] In the sector of production, it is of great importance for a producer to place its product in the market before its competitors. The producer may gain a competitive advantage by moving first in the market.[91] However, in reality, moving first means risk, because the product

[89] For an overview of the diffusion of 3D printing in different industrial sectors, see Laplume, André O., Bent Petersen, and Joshua M. Pearce. "Global value chains from a 3D printing perspective." Journal of International Business Studies 47, no. 5 (2016): 595-609.

[90] Bak, David. "Rapid prototyping or rapid production? 3D printing processes move industry towards the latter." Assembly Automation 23, no. 4 (2003): 340-345.

[91] See Weller et al. (2015), supra note 9.

may bear defects or fail to satisfy potential consumers. In order to avoid such risks, the producer has to obtain the mould of the product first and conduct a variety of tests, making sure that the product will be reliable and safe. Therefore, if a method can be found to shorten the lead time or lower the cost of moulding, it will greatly improve the producer's ability to execute its market strategy.[92]

As mentioned at the beginning of this chapter, one of the initial goals of 3D printing was to simplify prototyping activities. A specific product can be prototyped in a relatively short time and at a considerably lower cost with 3D printing compared to moulding in traditional mass production. To be specific, complexity under 3D printing is nearly free.[93] Design changes will not give rise to substantial increases in costs and lead times.[94] Professional companies that specifically focus on helping producers to prototype their products in a costless way have been set up. For instance, *Fast Radius* is an SME specialising in providing producers with fast and qualified prototyping solutions.[95] In cooperation with *UPS*, one of the largest delivery and supply chain management companies in the world, *Fast Radius* aims to add value by shortening the lead times of manufacturers. This business has proven to be successful. By the end of October 2019, it had finished an early-stage venture capital (series B) investment of 67.3 million dollars.[96]

Compared to traditional moulding processing, faster prototyping also enables manufacturers to carry out a higher number of tests of their designs. A successful example in this area is the collaboration between the world-famous sports company *Adidas* and *Carbon*. Traditionally, a shoe manufacturer can only afford three to five redesign cycles before finalising the ultimate design of

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[92] Petrovic, Vojislav et al. "Additive layered manufacturing: sectors of industrial application shown through case studies." International Journal of Production Research 49, no. 4 (2011): 1061-1079.

[93] Conner, Brett P. et al. "*Making sense of 3-D printing: Creating a map of additive manufacturing products and services.*" Additive Manufacturing 1 (2014): 64-76.

[94] As what is summarized by Conner et al., "By eliminating the need for tooling and fixturing, these printed prototypes are more cost-effective and take far less time (hence "rapid") than conventionally manufactured prototypes." See Conner et al. (2014), supra note 93, at 66; see also Campbell et al. (2011), supra note 12, at 6; Bernard, Alain, and A. Fischer. "New trends in rapid product development." CIRP Annals 51, no. 2 (2002): 635-652.

[95] For more information, see: https://www.fastradius.com/about. Visited on April 1st, 2019.

[96] See: https://www.crunchbase.com/organization/fast-radius-inc. Visited on October 7th, 2019.

a shoe. By applying 3D printing to the prototype process, however, *Adidas* can improve its design process by refining over 50 lattices for the midsole.[97]

As a way of rapid manufacturing, 3D printing also has important implications for the logistics sector. Traditionally, maintaining a network of inventory can be very costly because warehouses are needed in order to store large quantities of semi-finished and finished products. Also, transferring products from one place to another can generate considerable cost.[98] With the application of 3D printing, companies in the logistics sector can arrange their inventory network and eliminate some of their warehouses.[99]

2.3.2. Tools and gadgets

Along with its traditional contribution to rapid manufacturing, 3D printing is showing significant potential in offering solutions for end-use products. People cannot live without essential tools and gadgets, and there are endless examples. Hooks are necessary when we want to fix objects to walls; hammers and screwdrivers to assemble furniture; adapters to charge a laptop or a phone in different countries. These tools and gadgets can easily be obtained with the adoption of 3D printing.

With 3D printing, a person can customise a tool in a flexible way to align it perfectly with its intended use. In this sense, using 3D printing to customise tools and gadgets can make life easier. The non-complex nature of tools and gadgets implies that a variety of parties, ranging from individuals with average mechanical knowledge to SMEs and big companies, can participate. The level of imagination is evidenced by current examples. On open-source platforms like *Thingiverse* or on the online marketplaces focusing the sales of CAD files like *Pinshape*, many designs for tools are offered by individuals (see Figure 3 and Figure 4). In addition, start-ups that are focusing on smart tool solutions have also been established. For example, *Rehook* is an SME selling a tool

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[97] For more details on this case, see: https://www.carbon3d.com/case-studies/adidas/. Visited on April 1st, 2019.

[98] See Berman (2012), supra note 21.

[99] Ryan, Michael J, et al. "*3D printing the future: scenarios for supply chains reviewed.*" International Journal of Physical Distribution & Logistics Management 47, no. 10 (2017): 992-1014.

that can help cyclists in multiple ways, such as getting the chain back on the bike within a few seconds and spinning their gears easily.[100]

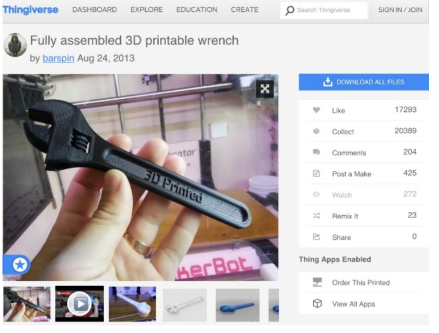

Figure 3: A 3D-printable spanner from the online platform Thingiverse [101]

Figure 4: A 3D-printable knife from the online marketplace Pinshape [102]

[100] For more details, see: https://www.rehook.bike/. Visited on April 15th, 2019.

[101] Source: https://www.thingiverse.com/thing:139268. Visited on April 15th, 2019.

[102] Source: https://pinshape.com/items/19232-3d-printed-plastic-knife-model. Visited on April 15th, 2019.

2.3.3. Wearables

3D printing also shows considerable potential in the market of wearable devices, which are perceived as improving comfort and user satisfaction.

Obtaining a CAD file that is customised to someone's feet is not difficult. Many start-ups have been set up to capture value with a personal digitalising model.[103] In addition, transposing the digital model into the corresponding physical item is straightforward. The collaboration between *Adidas* and *Carbon* is an example. In order to meet demands from athletes, *Adidas* seeks solutions for a higher performance midsole which includes lattices in a stiff but resilient elastomer that returns energy very effectively.[104] This requirement relates to an intricate inner design that is very difficult to accomplish with traditional production. However, this stringent need can be met with the application of 3D printing. As a leading 3D printing company that focuses on providing polymeric solutions, *Carbon* handles this problem in a holistic way (See Figure 5).

Figure 5: 3D-printed midsole for Adidas [105]

[103] One example of offering this service is Fitstation. People can easily stop by a Fitstation store and get the customized digital model of their feet. For more information, see: https://www.fitstation.com/. Visited on April 6th, 2019.

[104] See: https://www.carbon3d.com/case-studies/adidas/. Visited on April 6th, 2019.

[105] Source: https://techcrunch.com/2018/01/18/adidas-joins-carbons-board-as-its-3d-printed-shoes-finally-drop/. Visited April 6th, 2019.

In fact, customising trainers with 3D printing is not limited to companies. Ordinary individuals can do the same. The complete process from digital design to physical fabrication is shared on YouTube.[106]

Another area that is increasingly embracing 3D printing is the production of earbuds. Like feet, the structure of ears could be very different from person to person. A standard set of earbuds should allow people to enjoy music in a physically comfortable way. As 3D printing can add complexity and variance at nearly zero cost,[107] producing earbuds to meet the customised demand of users becomes possible. On open-source platforms, people are sharing the step-by-step method of customising earbuds.[108] With state-of-the-art technology, producing a pair of earbuds can be achieved on a desktop-level 3D printer (Figure 6). For example, *Formlabs* offers a complete guide on how to 3D-print earbuds with its 3D printer. In this case, customising any additional pair of earbuds only generates an additional cost of raw materials, which is only 3 to 4 dollars.[109]

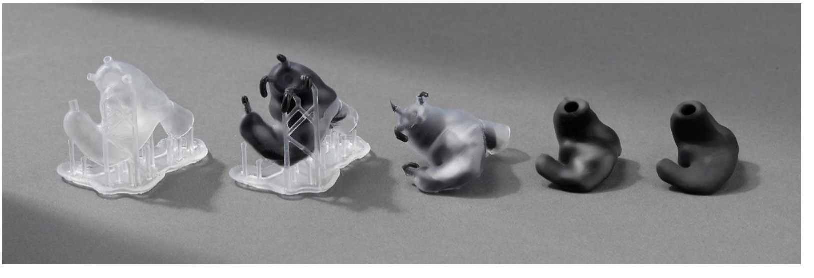

Figure 6: Earbuds that are customised by desktop-level 3D printers[110]

[106] For the reference to how it works, see: https://www.youtube.com/watch?v=zt4xM5zRn-U. Visited on April 10th, 2019.

[107] This proposition will be explained under Section 3.1.2 in Chapter 3.

[108] For example, an individual shares a complete guide on how to customize a pair of earbuds on 15 steps. See: https://www.instructables.com/id/3D-Printed-Earbuds/. Visited on April 16th, 2019.

[109] For more information, see: https://formlabs.com/blog/custom-earbuds-manufactured-with-3d-printing/. Visited on April 16th, 2019.

[110] Source: https://formlabs.com/blog/custom-earbuds-manufactured-with-3d-printing/. Visited on April 16th, 2019.

Other areas also reflect the customised role of 3D printing. For instance, Arruda and Carvalho in their research pointed out that 3D-printed wearables serve as a critical extension of the surface of the body. By taking 3D-printed gloves as an example, they found that wearables are easy to make with an FDM printing process by desktop printers.[111]

2.3.4. Utility components

3D printing technology also fits into many mechanical sectors, the most prominent of which are providing automotive components and even durable parts for the aerospace industry. By replacing some car components with the 3D printed equivalent, their capacity and performance can be enhanced.[112] For example, *Prodways* is a fabrication start-up offering high-quality car components. A part used in a car engine can easily be produced by 3D printing; the mechanical properties of the component will not be compromised since the material (i.e., PA6) used for fabrication is thermally stable. Compared to a part that is manufactured by traditional methods, a 3D-printed part can also feature a complex inner structure and reduced weight.[113] In addition, there has recently been growing interest in 3D printing in the aerospace industry in areas ranging from aero engines parts to cabin brackets.[114]

Building electronic components is another area where 3D printing shows promise. Many of the related parts can be finished to a level of high quality with 3D printing. For example, *Beta-layout* is a German company that offers customised solutions for electronic components, ranging from the printed circuit board to stencils and front panels.[115] In another example, *Aptiv* offers a polymer-based solution with 3D printing to produce high-quality cable, which is suitable for electrical and

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[111] Arruda, Luisa M., and Helder Carvalho. "3D Printing as a Design Tool for Wearables: Case Study of a Printed Glove." In Machado, José Mendes et al. (eds.) INTERNATIONAL CONFERENCE ON INNOVATION, ENGINEERING AND ENTREPRENEURSHIP, pp. 192-198. Springer, Cham, 2018.

[112] Savastano, Marco, Carlo Amendola, D. Fabrizio, and Enrico Massaroni. "3-D printing in the spare parts supply chain: an explorative study in the automotive industry." In Caporarello, L. et al. (eds.) DIGITALLY SUPPORTED INNOVATION: A MULTI-DISCIPLINARY VIEW ON ENTERPRISE, PUBLIC SECTOR AND USER INNOVATION, pp. 153-170. Springer, Cham, 2016.

[113] See: https://www.prodways.com/en/industrial_segment/automotive/. Visited on 19th April 2019.

[114] See Bogue, Robert. "3D printing: the dawn of a new era in manufacturing?." Assembly Automation 33, no. 4 (2013): 307-311.

[115] See: https://uk.beta-layout.com/. Visited on 22nd May 2019.

optic connections in an ocean environment.[116] In this example case, the printed cable offers advantages over cable that is produced using traditional methods, since it offers improved environmental resistance and lower unit cost.

2.3.5. Medical applications

Customised appliances are desirable in healthcare. By using 3D printing, a wide range of treatments can be improved.[117]

At present, medical uses like hearing aids and dentistry are the areas that are adopting most 3D-printed appliances. In dentistry alone, sales of $780 million had been achieved by 2015.[118] In addition, areas like prosthetics also have a bright future in collaboration with 3D printing. Compared with traditional techniques, prosthetic appliances built by 3D printing feature intricate and highly customised contours, which help patients who suffer from amputations to gain a biomimetic experience. It is estimated that employing 3D printing would be most cost-effective in cases where small-sized implants and prosthetics are needed. In situations where the medical items are demanded in low volumes but with high complexity, 3D printing is also popular.[119]

Bioprinting is a recent innovation. With the application of 3D printing, two-dimensional tissues, hollow tubes, and even solid organs can be produced to help improve people's health conditions.[120] At present, many applications are still at the laboratory stage and more time is needed to put them to practical use. However, it is estimated that progress will be rapid as more research teams participate in this burgeoning area.[121] Take the 3D-printed kidney as an example. Scientists in 2013

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[116] See: https://www.carbon3d.com/case-studies/aptiv-qualifies-carbon-for-stringent-parts/. Visited 19th April 2019.

[117] See Awad, Atheer, Sarah J. Trenfield, Simon Gaisford, and Abdul W. Basit. "3D printed medicines: A new branch of digital healthcare." International journal of pharmaceutics 548, no. 1 (2018): 586-596.

[118] SmarTech, 3D Printing Industry Reports, 2015. Available at: https://3dprintingindustry.com/news/smartech-report-3d-printing-in-dental-market-to-reach-3-1-billion-by-2020-51971/. Visited on April 19th, 2019.

[119] Choonara, Yahya E., Lisa C. du Toit, Pradeep Kumar, Pierre PD Kondiah, and Viness Pillay. "3D-printing and the effect on medical costs: a new era?." Expert review of pharmacoeconomics & outcomes research 16, no. 1 (2016): 23-32.

[120] Murphy, Sean and Anthony Atala, "*3D Bioprinting of Tissues and Organs*", Nature Biotechnology, Volume 32:8, 2014.

[121] In recent years, public offerings have been initiated at an increasing rate in the bioprinting area. For example, "Organovo", a bioprinting corporation founded in 2007, has successfully got public offerings and started to trade on

created the first 3D-printed living kidney that can be transplanted.[122] In early 2018, 3D printing was firstly used in an operation which supports a precise kidney transplantation from a father to his daughter.[123]

Numerous stakeholders are involved in activities that apply 3D printing in the medical sector. Firstly, supportive stakeholders, who offer professional 3D printers and biocompatible materials, laid a technological foundation to stimulate the application of 3D printing. For example, *EnvisionTEC* is a 3D printer producer that offers 3D printers and materials that can help doctors improve their treatments. Using a professional "P3 DSP" 3D printer, a clinic can print 35 different ear shells or 18 different ear moulds within an hour.[124] Doctors can also have appliances printed by external devices. Enterprises that own 3D printers take over the printing process. *Invisalign*, one of the largest enterprises focusing on the 3D-printed tooth, produces more than 50,000 appliances per day.[125] The trend for decentralised key stakeholders is also observed in the medical sector. Individuals can contribute their medical expertise or 3D printing devices through various intermediaries to help people who suffer from diseases. For instance, through *E-NABLE*, individuals seeking a CAD file of a hand or a related printing service are directed to individuals who have such expertise in the community.[126] In this regard, medical appliances manufacturing and medical services are both decentralised with the introduction of 3D printing.

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the NASDAQ stock market since 2016. It develops even faster since then with the launch of subsidiaries on commercial operations of bioprinting.

[122] See, Feinberg, Ashley, "*Scientists Can Now 3D Print Transplantable, Living Kidneys*", at https://gizmodo.com/scientists-can-now-3d-print-transplantable-living-kidn-1120783047. Visited on June 6th, 2017.

[123] See Rushabh Haria, "*Kidney Transplant Using 3D Printing Marks as a Medical First in Belfast*", January 22nd, 2018, at https://3dprintingindustry.com/news/kidney-transplant-using-3d-printing-marks-medical-first-belfast-127743/. Visited on May 5th, 2018.

[124] See EnvisionTEC, https://envisiontec.com/3d-printing-industries/medical/hearing-aid/. Visited June 6th, 2017.

[125] Mckinsey Global Institute, "*Disruptive technologies: Advances that will transform life, business, and the global economy*." 2013.

[126] See E-NABLE, http://enablingthefuture.org/. Visited on April 19th, 2019.

Chapter 3. 3D Printing as a Social Disruption: Value Creation and Risk Exposure

The discussion in Chapters 1 and 2 explained why 3D printing is promising from the technical perspective and how the market is gradually accepting it. On that basis, this chapter continues to explore the disruption caused by 3D printing and its implications for the product risk.

The discussion of Chapter 3 proceeds as follows. Section 1 starts the discussion from a value-creation perspective. It firstly sheds light on how the value is created in traditional production. The extent to which 3D printing is transforming the conventional chain of value creation is explained in this section. In Section 2, the discussion shifts to the business models that are adopted to capture the value created by 3D printing. In the scenario of 3D printing, consumers can choose the CAD file from a CAD file designer and then bring it to a fabricator to print out the final product. The role of consumers stands out in this so-called "separation" business model, because it is the consumers that are responsible for coordinating and combining the different CAD file designers and fabricators. Therefore, Section 3 pays special attention to the prevailing "separation" models, the aim of which is to categorise the different ways that consumers can rely on to obtain the CAD files and to access the fabrication service.[127] Section 4 summarises the potential risks posed by different business models.

3.1. Value creation in the production sector

Value creation is the starting point for all businesses. A company cannot survive in the market unless it creates and captures sufficient value in support of its operations.[128] Value can be added

[127] The brief introduction of different business models can also be seen in the appendices.

[128] See Porter, Michael E. COMPETITIVE ADVANTAGE: CREATING AND SUSTAINING SUPERIOR PERFORMANCE. Free Press, 1998, at 36-47.

to many different activities, which are distributed along the so-called value chain. The concept of the value chain was first proposed and systematically analysed by Michael Porter, according to whom a product passes through a chain of activities before it reaches consumers and these activities constitute the units where value is added.[129] Parties will adopt various strategies by assessing their comparative advantages concerning relevant activities. This first section delves into the issue of how value is created in the context of traditional manufacturing and more importantly, how value creation is changed in the context of 3D printing.

3.1.1. Value creation in traditional mass production

In general, all activities along the value chain can be classified as either primary activities or supportive activities.[130]

Creating value based on primary activities

Primary activities include all of the activities in a horizontal direction, from inbound logistics, operations, outbound logistics, and marketing and sales through to service.[131] A single party may engage in all activities along the chain, which means that they are responsible for all the activities based on their own efforts. This scenario was widely observed in ancient times when productivity was extremely low. At that time, a craftsman obtained raw materials from nature and then made the final product, which was ultimately placed on the market. No third party was involved in this process.

As productivity increased and products became increasingly complex, producers gradually found that they could optimise the production process by outsourcing some activities to external parties. The reason why they made this choice was that a specific unit in the chain of activities could be extremely costly for them. If producers were rational, they would admit that others may be better

[129] "[Comparative advantage] stems from the many discrete activities a firm performs in designing, producing, marketing, delivering, and supporting its product". As Porter further articulated, "each of these activities can contribute to firm's relative cost position and create a basis for differentiation." See Porter (1998), supra note 128, at 36.

[130] See Porter (1998), supra note 128, at 45.

[131] See Porter (1998), supra note 128, at 36-52.

able to capture the relevant value at a lower cost. As a result, producers chose to invest their limited resources in the units where they can add the highest value. The fragmentation of the value chain became especially significant in the aftermath of the Industrial Revolution. As various resources were controlled by entirely different parties, the pattern of value creation was accordingly transformed. For instance, the party who controlled raw materials held a natural advantage of being able to specialise. The party who owned a fleet of ships was expected to be the best at transporting cargo. As a result, value creation was fragmented to a large extent along the chain of primary activities. As the social division of labour deepened, the producer who had been skilled at handling everything along the supply chain turned into a "pure producer" who only focused on manufacturing activities. For the activities other than production, producers usually seek to establish a relationship with the parties who add such value most efficiently. Therefore, a linear supply chain based on contractual relationships is formed at the same time as value-added activities becoming fragmented along the value chain.

Creating value based on supportive activities

In addition to primary activities, supportive activities are also crucial in terms of distinguishing one party from another. Whenever various parties attempt to provide the same goods or services, they are de facto competing for a better position to capture the value around those goods or services. In a market where goods and services can easily be substituted, value is mainly created through economies of scale. In this regard, if a party can provide the goods or services at the lowest price, then it holds a competitive advantage. In other words, parties which provide the same goods or services but at a higher price can only capture the residual value. The factors that lead to the differences between parties which offer (substitutive) goods or services constitute the supportive activities where a producer can add extra value. According to Porter, these activities include firm infrastructure, human resource management, technology and procurement.[132]

The fact that supportive activities have a substantial impact on value creation motivates producers, as well as other parties, to invest in new technologies and to optimise their organisational structures. In brief, in a market where goods or services can be easily substituted, the party that adopts a

[132] See Porter (1998), supra note 128, at 36-52.

modern organisational structure and exploits advanced technologies is expected to gain a competitive advantage over others. Such factors are further perceived as a *threshold* for market entrants. This means that a party needs to keep improving supportive activities to maintain its competitive advantage in the market. If a party fails to improve its supportive activities, it will be surpassed by its competitors and might ultimately be ejected from the market. Therefore, efforts used to capture the value of production clearly distinguish producers. Mass producers that can afford the associated costs will survive, whereas small producers run a higher risk of being discriminated against and pushed out of the market.

The balance between scale and uniqueness when creating value in traditional production

In a market where goods and services cannot be easily substituted, supportive activities do not matter a lot to the success of a company. In such circumstances, as different goods and services are sufficiently distinguished from each other, value is created in the event that a party can offer something *unique* to others. This uniqueness is perceived as a competitive advantage, and it offsets the disadvantages brought about by a lack of economies of scale.[133]

Providing unique goods or services is not easily achieved in practice. With traditional manufacturing, where profits are generated by leveraging scale, providing uniqueness means purchasing a new set of machines, employing new experts, or searching for new upstream or downstream partners. In this regard, any further movement toward uniqueness means a deviation from scale economies and a considerable increase in costs.[134] Therefore, while providing different kinds of product generates uniqueness and promises the producer a competitive advantage, huge costs may also arise. Taking this dilemma into account, a producer has to find a balance between scale and uniqueness.

In reality, a producer tends to produce as much uniqueness as it can on the basis that it has gained some advantages from the scale. For example, a bookseller will try to place as many different kinds of books in the bookstore as it can. However, as the capacity of the bookstore is limited, the

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[133] Berman (2012), supra note 21.

[134] Petrick, Irene J., and Timothy W. Simpson. "*3D printing disrupts manufacturing: how economies of one create new rules of competition.*" Research-Technology Management 56, no. 6 (2013): 12-16.

bookseller has to choose the bestsellers and place these most popular books in a conspicuous spot. While Amazon has moved physical bookstores onto the Internet and thereby increased the capacity of the bookstore by showing incredibly large numbers of books, it still cannot provide all books in existence on its website due to the capacity of its physical warehouses. Consequently, Amazon chooses the top hundreds of thousands of books, and it has to leave out others. As this is a traditional business model, books that are enjoyed by minorities and older editions are less preferable to Amazon.

The balance between scale and uniqueness also has a significant impact on the demand side. Producers are always more willing to capture the enormous demands of the mass market rather than the exceptional demand of a niche market. That said, the exceptional demand in niche markets in the form of an aggregate is a considerable number that could even surpass the mass-market demand. However, as capturing such a dispersed demand is costly under the current pattern of production, producers have to opt to neglect it. As a result, unique demand is difficult to satisfy with traditional production which is driven by economies of scale. As Anderson notes, small demands in total serve as a "long tail" behind mass demands.[135] Massive value is present there, but it can never be fully captured since the marginal cost to pursue a variance in product could be extremely high.[136]

To conclude this subsection, a party will find a place in the chain of production, provided that it can create value in related primary or supportive activities. For a producer, the manufacturing process serves as the primary part so far as creating value is concerned, indicating that value is mainly captured by economies of scale. Hence, gaining value from uniqueness is not easily achieved and only larger entities, rather than individuals or SMEs, can engage in traditional production.

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[135] Anderson, Chris. The long tail: Why the future of business is selling less of more. Hachette Books, 2008, at 15-26.

[136] The way to lean to the demands in the niche market is to transform the business model. For example, Amazon has to permit various bookstores to free-ride his platform by enabling them to show their inventory on the website. By doing so, the users would be stuck to Amazon.

3.1.2. The transformed value creation in the context of 3D printing

Compared with traditional mass production, value creation in 3D printing has some new features. It is these new features that pose risks to the sector of production and provide further grounds for rethinking the performance of legal instruments when dealing with product risk. The following provides an in-depth analysis of the disruptive power of 3D printing in production, highlighting its relevance to product safety.

Complexity is free with 3D printing

From the technical perspective, the most disruptive transformation generated by 3D printing is that any complexity added by a producer is nearly costless.[137] The cost per unit under traditional manufacturing is expected to increase as the scope of products expands. This is because developing any additional new units requires an extra investment, which ranges from constructing new moulds to purchasing new machines and employing relevant experts.[138] Traditional producers compete for the value of standard products. They may hesitate to expand their business not only because any expansion will give rise to additional cost, which may not be covered by the generated demands.[139] With conventional production, the cost savings that result from production diversity (i.e. "economies of scope") can only be achieved by combining two or more product lines in one firm rather than operating them separately in different organisations.[140] Therefore, since shifting the business model from standard products to customised products indicates an increase in cost per unit, producers tend to limit the expansion of the production scope.

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[137] This disruption caused by adopting 3D printing can also be identified in literature, such as Conner et al. (2014), supra note 94, at 71, Redwood et al. (2017), supra note 13, and Attaran, Mohsen. "Additive manufacturing: the most promising technology to alter the supply chain and logistics." Journal of Service Science and Management 10, no. 3 (2017): 189-205, at 19.

[138] Teece, David J. "Economies of scope and the scope of the enterprise." Journal of economic behavior & organization 1, no. 3 (1980): 223-247; Petrovic et al. (2011), supra note 94.

[139] Ben-Ner, Avner, and Enno Siemsen. "Decentralization and localization of production: The organizational and economic consequences of additive manufacturing (3D printing)." California Management Review 59, no. 2 (2017): 5-23.

[140] Panzar, John C., and Robert D. Willig. "Economies of scope." The American Economic Review 71, no. 2 (1981): 268-272.

This scenario is no longer applicable when 3D printing is introduced. In the context of 3D printing, the cost per unit is relatively stable. An expansion of the scope of production is at the expense of an extra unit of raw materials. Beyond that, other costs (e.g. purchasing new machines, adjusting organisational structure, investing R&D, and employing relevant experts) are not significantly generated.[141] In this sense, any additional complexity in the context of 3D printing is nearly free. This transformation has a significant implication in light of shifting the focus of the business model from the mass market to the niche market. The value generated in customisation can be captured at a low cost with the adoption of 3D printing. The divergence in the cost per unit between traditional production and 3D printing could be even larger as the scope of production expands.[142]

In theory, there will be a crossover point at which 3D printing starts to have a lower cost per unit than traditional production as the scope of production expands.[143] Traditional production is shown as having a comparative advantage over 3D printing on the left side of this point. All producers are competing against each other to capture the value in this area. They will take strategic approaches to evaluate the investments in supportive activities and the resulting increased profits. In comparison, beyond this point, 3D printing is shown as having a comparative advantage over traditional production.

With 3D printing, since an increase in complexity as well as an expansion of product variety is associated with a fixed cost per unit, 3D printing shows a competitive advantage over traditional methods. In other words, beyond the crossover point, infinite product variety can be achieved without significantly increasing the cost per unit.[144] Thus, the adoption of 3D printing enables parties to capture the value of customisation at a lower cost.[145]

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[141] This is shown as the orange line in Figure 1.6. See Attaran, Mohsen. "The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing." Business Horizons 60, no. 5 (2017): 677-688, at 682.

[142] Diegel, Olaf, Sarat Singamneni, Stephen Reay, and Andrew Withell. "Tools for sustainable product design: additive manufacturing." Journal of Sustainable Development 3(3) (2010):68-75; Campbell et al. (2011), supra note 12; Gershenfeld, Neil. "How to make almost anything: The digital fabrication revolution." Foreign Aff. 91 (2012): 43; Conner et al. (2014), supra note 94, at 68; Ng, Irene, et al. "*Contextual variety, Internet-of-Things and the choice of tailoring over platform: Mass customisation strategy in supply chain management*." International Journal of Production Economics 159 (2015): 76-87.

[143] See Redwood et al. (2017), supra note 13, at 9.

[144] Weller et al. (2015), supra note 9.

[145] Lipson and Kurman (2013), supra note 9; Attaran, supra note 141.

In brief, this part reveals the place where 3D printing creates value and where parties using 3D printing can strive to capture the value.[146] The customised production rather than the standard one is thus the driver of the next wave of the production revolution.[147] From the risk exposure perspective, the trend of customisation increases the difficulty of monitoring the activities of actors.

Scale economies do not necessarily drive value creation

Another noteworthy disruption caused by 3D printing, which is also related to the discussion before, is that value creation is not necessarily driven by the economies of scale.

The demand for a specific kind of product varies among consumers. The more customised a product is, the lower the demand. Many producers are willing to capture value in the mass market where the most demand is found (Producer A). Fewer producers (Producer B) can meanwhile capture the value in the niche market since less demand is identified and the cost per unit increases. Even fewer producers can build and extend their business solely in the niche market (Producer C) since the cost per unit at that point will become extremely high, which may even exceed the rewards. Therefore, the competence of different producers is distinguishable in the traditional market. It is the Producer C rather than the Producer A and B that have the capacity to capture value as the cost per unit keeps increasing with the expansion of the scope of production. For many other producers, they have to compete with each to capture the demand in the mass market. Only the most powerful producers can gain a competitive advantage, while those less competent ones would be gradually pushed out of the market.

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[146] By building up models, the cost-effective on 3D printing in the niche market has been confirmed by engineers. See Hopkinson, Neil, and P. Dicknes. 2003. "Analysis of rapid manufacturing—using layer manufacturing processes for production." Proceedings of the Institution of Mechanical Engineers." Journal of Mechanical Engineering Science 217, no.1:31-39; see also, Ruffo, Massimiliano, Chris Tuck, and R. Hague. 2005. "Cost estimation for rapid manufacturing-laser sintering production for low to medium volumes." Proceedings of the Institution of Mechanical Engineers." Journal of Engineering Manufacture 220, no. 9:1417-1427.

[147] Hopkinson, N., R. J. M. Hague, and P. M. Dickens. RAPID MANUFACTURING: AN INDUSTRIAL REVOLUTION FOR THE DIGITAL AGE. Chichister, England: John Wiley and Sons, Ltd (2006). See also Kietzmann, Jan, Leyland Pitt, and Pierre Berthon. "Disruptions, decisions, and destinations: Enter the age of 3-D printing and additive manufacturing." Business Horizons 58, no. 2 (2015): 209-215.

The situation is totally different when it comes to 3D printing. As the previous analysis indicates[148], 3D printing has a competitive advantage in the niche market. In this scenario, as the cost per unit is relatively constant in terms of expanding the scope and complexity of the product, a producer does not need to fixate their business on specific activities. Instead, it can explore an extensive scope of products as the very low additional cost per unit will not be an obstacle. In other words, a party can flexibly shift from one product to another at any time in the era of 3D printing. Therefore, whether a party can win a competitive place in the niche market is primarily determined by the issue of whether or not they are able to satisfy a wide range of customised demands.[149] If a producer can detect a field where only it can offer a solution in support of a specific demand, it is capable of finding a position in the long tail of the niche market. The dilemma and balance of "scale-scope" is therefore no longer a problem with 3D printing.[150]

From the risk exposure perspective, the arising scope economies tremendously transform the pattern of production. Besides mass production, the production that is organised in a non-industrial way also makes pose great risks to the society. Therefore, it is necessary to study whether the current legal regime can efficiently deal with the risk posed by the increasing non-industrial methods of production.

The engagement of non-professionals in capturing the created value

As 3D printing releases the potential in the niche market and largely removes scale economies, many parties other than traditional mass producers can engage in production-related activities.[151]

As economies of scale do not constrain the involved parties from competing for a position as shown in the niche market, they are able to engage in production-related activities, such as contributing to a specific idea, providing a customised CAD file and transposing a CAD file into an object.[152]

148 The analysis under the title of "complexity is free with 3D printing" in this section.

149 Petrick et al. (2013), supra note 134.

150 Weller et al. (2015), supra note 9.

151 See Attaran (2017), supra note 141; Rayna and Striukova (2016), supra note 49.

152 Campbell, R. et al. "Design evolution through customer interaction with functional prototypes." Journal of Engineering Design 18, no. 6 (2007): 617-635. Rayna, Thierry, Ludmila Striukova, and John Darlington. "Co-creation

Therefore, not only are traditional producers involved, but also SMEs and even ordinary individuals can take part in 3D-printing-related activities.[153]

At the moment, it is not unusual to hear of individuals engaging in designing and fabricating activities on their own.[154] Large communities consisting of "makers" are widely seen online.[155] The expanding group of non-professionals and the risk posed by these parties greatly challenges the traditional paradigm set for dealing with the accidents caused by product risks. How to provide these small but widespread non-professionals with an incentive to behave appropriately has turned out to be one of the most important questions asked in this research.

The separation of digital designing and physical fabrication

In traditional production, the primary activities where value can be added by producers are still limited to the physical fabrication process. This pattern, however, has been largely transformed with the adoption of 3D printing. Specifically, as the technical features in a CAD file determine the quality and function of the ultimate product to a large extent, a party can de facto add substantial value if it creates a CAD file that contains instructions for the subsequent printing process.[156]

The separation of digital designing activities and physical fabrication activities reflects a paradigm shift in the sector of production. A party does not necessarily have to develop a "one-stop" business that covers all of the production processes. Instead, a party can choose to only focus on designing

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and user innovation: The role of online 3D printing platforms." Journal of Engineering and Technology Management 37 (2015): 90-102. See also Conner et al. (2014), supra note 94; Attaran (2017), supra note 141.

[153] Literature has evidenced that the majority of SMEs with long experience of 3D printing operation increases their competitiveness. See Khorram Niaki, Mojtaba, and Fabio Nonino. "Impact of additive manufacturing on business competitiveness: a multiple case study." Journal of Manufacturing Technology Management 28, no. 1 (2017): 56-74.

[154] Lipson and Kurman (2013), supra note 9. See also Keymolen, Esther. "The Focal Practice of 3D Printing." In Van den Berg, Bibi, Simone Van der Hof, and Eleni Kosta (eds.) 3D PRINTING: LEGAL, PHILOSOPHICAL AND ECONOMIC DIMENSIONS. Vol. 26. Springer, 2016, at 99-116.

[155] Anderson, Chris. MAKERS: THE NEW INDUSTRIAL REVOLUTION. Crown Business, 2014, at 53-60. See also Kostakis, Vasilis, and Marios Papachristou. "Commons-based peer production and digital fabrication: The case of a RepRap-based, Lego-built 3D printing-milling machine." Telematics and Informatics 31, no. 3 (2014): 434-443.

[156] Mueller, Bernhard. "Additive manufacturing technologies–Rapid prototyping to direct digital manufacturing." Assembly Automation 32, no. 2 (2012); Holmström, Jan et al. "The direct digital manufacturing (r) evolution: definition of a research agenda." Operations Management Research 9, no. 1-2 (2016): 1-10.

CAD files or printing out the final products. As a consequence, the whole process of production could be accomplished by two or even more parties who are strangers to each other.[157]

In practice, this paradigmatic shift has a great impact on the transformation of business models. Specifically, various business models have been set up to help CAD file makers and 3D printing service providers to capture the value created by 3D printing. From the risk exposure perspective, all the parties that are involved in either digital modelling or physical fabrication activities should be provided with an incentive to behave appropriately, and they should be ensured methods to shift risk when necessary.

The importance of consumers and information

The separation of digital designing and physical fabrication also indicates the increasingly important role of consumers. To better capture the value created by 3D printing, the digital designing and physical fabrication activities could be respectively accomplished by different parties. In this pattern, it is the consumers that serve as the party to coordinate the process of production.

From the risk exposure perspective, the behaviour of consumers could influence the amount of social welfare. By undertaking different combinations of digital modelling services and 3D printing services, the decision-making of consumers could lead to social welfare differently. Therefore, specific instruments should be provided to consumers to induce and help them to make decisions efficiently. The fact that the linear supply chain is replaced by an agile one and that the relevant institutional framework is mostly missing leads to a situation where new mechanisms and intermediaries are demanded to connect the demand with the supply and to reveal more credible information.[158]

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[157] Heine, Klaus, and Li Shu. "What Shall we do with the Drunken Sailor? Product Safety in the Aftermath of 3D Printing." European Journal of Risk Regulation 10, no. 1 (2019): 23-40.

[158] Many signals are offered in traditional production so that various parties are able to collect information, which helps them to develop a better understanding of product safety. Many cases are presented here in support of this viewpoint. The producers who are not eliminated from the market indicate that they invest enormously to be competent. The underlying information implies that such producers are capable of using advanced machines, adopting effective organisational structures or paying attention to post-sales service. Information is also disclosed with traditional production as relevant parties are linked to each other via the linear supply chain. In addition, the efforts that are taken

3.1.3. Summary

To summarise, this section has analysed the issue of how 3D printing disrupts the traditional value chain of production. First and foremost, value is created since an increase in complexity is nearly free and scale economies do not necessarily drive production. In this sense, the threshold of primary activities (e.g. designing and manufacturing) is significantly lowered. Secondly, value is created as the emergence of 3D printing has the potential to capture small demand on the long tail. Thirdly, the whole process of production is divided into digital designing activities and physical fabrication activities. This change increases the agility of the production by making it possible to have different parties who are strangers with each other work together to accomplish production. Last but not least, consumers are no longer bystanders of production. Instead, they are the coordinators between CAD file designers and fabricators.

More importantly, the discussion in this subsection has revealed how the disruptions caused by 3D printing have significant implications for product risk. Firstly, the removal of scale economies indicates that production can extend to the "long tail", where traditional mass production fails to reach. In addition, there is no longer a single "producer" who handles everything in the production process. Coordination problem might arise because the digital designing and physical fabrication activities are accomplished by different parties who are strangers to each other. Thirdly, non-professionals and consumers are unprecedentedly involved in capturing the value created by 3D printing. Therefore, appropriate instruments should be developed to ensure that the disruptions aforementioned will not deviate from the goal of deterrence and risk-shifting.

In practice, various business models have been established to help the stakeholders aforementioned to capture the value. In the next section, the extent to which these parties are involved in the specific business models is introduced in detail.

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by a producer to comply with regulations and acquire certifications as well as establish reputations also act as a process to reveal necessary information. See Heine and Li (2019), supra note 157.

3.2. Capturing value with 3D printing: the taxonomy of business models

The value created by 3D printing can be transposed to reality only if it is captured by specific parties through particular business models. In the context of 3D printing, all business models can be generally distinguished into one of two categories. Firstly, a consumer might go to an entity who has the ability to accomplish the whole process from digital modelling to physical fabrication. Alternatively, a consumer might choose to acquire the CAD file from one party and then have it printed out by another.[159]

3.2.1. The "one-stop" business model

Some firms are established to offer a one-stop solution for customers (hereinafter the "one-stop model"). This includes not only digital modelling but also physical fabrication – everything is accomplished within one entity. In this regard, 3D printing through the "one-stop model" is not distinctly different from traditional production. In reality, not every party has the capacity to embrace the "one-stop model"; only some professional fabricators are able to adopt this business model. Figure 7 briefly shows how the "one-stop model" works.

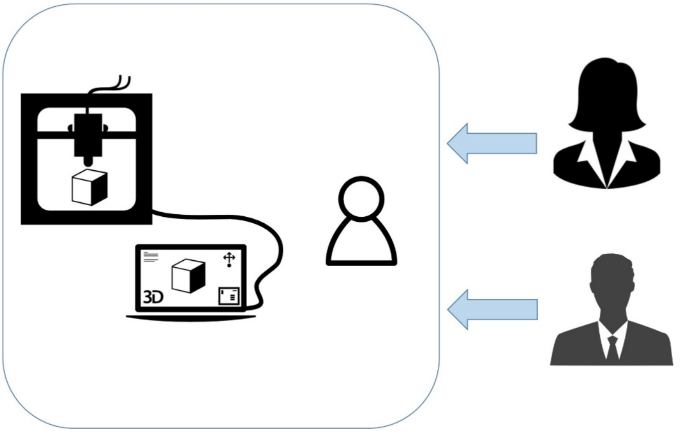

Figure 7: The "one-stop" business model

[159] The brief introduction of different business models can also be seen in the appendices.

In practice, the "one-stop model" is mostly adopted in the sector of customised medical devices, automotive components and so on. A typical example is the orthodontics treatment plan offered by *Invisalign*, which provides the whole set of services to help patients correct their teeth. In this scenario, a dentist uses a special *iTero Element* scanner to get a digital model of the teeth, which is sent to *Invisalign* at a later stage. The experts from *Invisalign* work with dentists to come up with the best solution. In this process, an advanced software program called *Clincheck* is employed to ensure that the customisation is precise. Once the digital model is finalised, the most advanced 3D printing techniques are applied by *Invisalign* for the physical fabrication. As a leading orthodontics service provider, by 2018, *Invisalign* was fabricating more than 50,000 parts per day.[160]

The "one-stop model" has also been adopted by some fabricators who offer a general 3D printing service. In this case, fabricators that are used to only focusing on fabrication activities may extend their business towards digital designing as well, especially when the CAD files offered by consumers need robust modification. For example, *Statasys Direct* is famous for its role in printing CAD files for consumers. However, in order to ensure that the solution can be manufactured and fits the exact needs of the consumer, *Statasys Direct* also offers a comprehensive digital modelling service.[161]

In essence, the "one-stop model" does *not* deviate much from the traditional way of manufacturing, because both of them focus on providing the final physical product to consumers. Therefore, the way that the "one-stop model" works does not reflect the transformation caused by 3D printing. It is reasonable to propose that the incumbent legal regimes that apply to traditional manufacturing would still be largely applicable to the "one-stop model" in the context of 3D printing. The "one-stop model" is not the main interest of this research.

[160] See: https://3dprintingindustry.com/news/hp-and-smiledirectclub-to-3d-print-20-million-3d-printed-clear-aligner-dental-molds-per-year-155862/. Visited on April 14th, 2019.

[161] See: https://www.stratasysdirect.com/manufacturing-services/design-services. Visited on 14th, 2019.

3.2.2. The "separation model"

As analysed before, one of the most prominent disruptions caused by 3D printing is that the whole process of production is divided into the digital designing process and the physical fabrication one.[162] This separation implies that consumers can freely combine the CAD file sources with printing services for the sake of maximizing their utilities. It is this "separation model" that *distinguishes* 3D printing largely from traditional manufacturing.[163]

In reality, assuming that parties who offer CAD files or printing services are as competent as traditional producers and that information can be smoothly conveyed among strange digital designers and fabricators as if they are different departments within the same entity, the separation model will not pose a special risk. These assumptions can however be distorted as the business models that the consumers rely on to obtain the CAD files and to access printing services are vastly different. Therefore, there is a pressing need to understand the concrete business models that relevant parties are involved in and to figure out the potential risk linked to each of these operations.

In recent years, the importance of business models regarding 3D printing has been increasingly recognised. Different kinds of categorisations have been proposed in the literature.[164] However, the literature on this topical issue is mostly based on the supply chain perspective. It does not examine the risks posed by this disruptive technology, nor does it identify the potential instruments that can deal with the associated problems.[165] Therefore, exploring the categorisation of different business models, which links with legal implications, turns out to be a crucial problem that should

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[162] See the discussion in Section 3.1.2.

[163] The brief introduction of different business models can also be seen in the appendices.

[164] For example, in a recent research Rogers et al. categorized the business models relating to 3D printing into three groups: (1) the business model focusing on generating a CAD file (generative service), (2) the business model focusing on printing the CAD file out (facilitative service), and (3) the business model providing the consumer with a marketplace to search for suitable CAD files (selective service). See Rogers, Helen, Norbert Baricz, and Kulwant S. Pawar. "3D printing services: classification, supply chain implications and research agenda." International Journal of Physical Distribution & Logistics Management (2016). Other literature focusing on the taxonomy of 3D-printing-related business models are: Rayna, Thierry, and Ludmila Striukova. "A taxonomy of online 3D printing platforms. In Van den Berg, Bibi, Simone Van der Hof, and Eleni Kosta (eds.) 3D PRINTING: LEGAL, PHILOSOPHICAL AND ECONOMIC DIMENSIONS. Vol. 26. Springer, 2016, at153-166.

[165] For example, in Rogers et al. (2016), while the authors distinguish "generative service" from other kinds of business models, they fail to dictate the differences within this specific service. In this regard, even for the purpose of obtaining a design, different methods can be further distinguished, which could result in a considerable divergence in terms of risk exposure, legal certainty as well as the potential liability. See Rogers et al. (2016), supra note 164**Error! Bookmark not defined.**.

be firstly set out. In the next section, how different business models are established under the "separation model" is introduced in detail.

3.2.3. Summary

To summarise, this section generalises the categorisation of the various business models that relevant actors rely on to capture the value created by 3D printing and that consumers rely on to acquire the final product. We can first distinguish all of the business models into one of two categories. One is called the "one-stop model" representing the case where a consumer can contact one actor who will take care of both the digital design and physical fabrication. This "one-stop model", as its name indicates, shows no significant difference from mass production. This is because all of the production processes (including digital designing and physical fabrication) are completed within a single entity.

The other type of business model is called the "separation model". This represents the case where a consumer has to contact the CAD file maker and fabricator respectively. It is this latter "separation model" that is the direct result of 3D printing's transformation in the production sector. As production activities are no longer completed within a single module, transaction cost and information asymmetry in the existence of coordinating risk allocation will increase.

Having understood that the "separation model" is the context where most disruptions take place, an in-depth interpretation of various business models is conducted in the following Section 3.3.

3.3. A closer look at the "separation model"

According to the different sectors where value is added, all business under the so-called "separation model" can be divided into two categories: the activities that are organised for digital designing and the activities that are related to physical fabrication. For convenience, these two kinds of activities are respectively named Model A and Model B in this thesis. Hence, *Model A* refers to the circumstance that a party only focuses on capturing value by offering CAD files, and *Model B* refers to the circumstance in which a party only focuses on capturing value by offering printing service. In practice, in order to have a final product, a consumer has to firstly reach out to a CAD file design under Model A. Then, s/he takes the obtained CAD file to the party who runs a printing business.

Provided that *information can be well conveyed* between the CAD file designer and the final product fabricator who respectively come from Model A and Model B, risk allocation will not be a big problem. This is because, ultimately, the relevant parties will find a way to distinguish which party is best positioned to bear the risk. However, in reality, this assumption may not hold. As the method used to obtain a CAD file or a final product can be largely different, there is a divergence when it comes to bargaining over the allocation of risk. In other words, as the designer under Model A and the fabricator under Model B are from different modules, most likely they are strangers to each other. As a result, the difficulty in allocating risk is also largely different when different business models are combined. Taking this divergence into account, it is necessary to further distinguish the different sub-models respectively under Model A and Model B.

There are three ways in which a consumer can gain a CAD file. Therefore, Model A can be further divided into three sub-models.

- ***Model A.1*** represents the situation where the CAD files are uploaded on an open-source platform. The key attribute of this business model is that consumers have free access to the CAD files and, more importantly, they can remix a CAD file and re-upload it. Therefore, it is mostly ordinary people and a portion of small-sized business that run their business based on Model A.1.
- ***Model A.2*** refers to a business where sellers offer CAD files in a virtual marketplace. This business model is also welcomed by ordinary individuals and SMEs. Consumers can pick the CAD files in an online market in the same way as if they are purchasing a product in a real market.
- ***Model A.3*** usually applies to the medium-or- large-sized entities who have the capacity to run an independent platform or who have a particular distributing channel that can be accessed by consumers.

After obtaining a CAD file, a consumer has three options to have it printed out. Model B can also be divided into three sub-models in practice.

- Firstly, like Model A.3, a fabricator can run an independent channel or set up an independent online platform to offer the printing service. This type of business model is categorised as ***Model B.1*** and it is normally adopted by larger entities who have the capacity to support operating such an independent supply channel.

- In addition, ***Model B.2*** represents the approach where a consumer reaches out to the fabricator through an online marketplace. In practice, the fabricators who capture the value in this business model are normally ordinary individuals and SMEs.
- Furthermore, there is a ***Model B.3***, in which a consumer does not directly with a fabricator. Rather, s/he has to rely on an *intermediary platform* (i.e. an agent), who owns no printers but will find out the most suitable fabricator on behalf of the consumer.

Figure 8 shows this distinction and explains how a consumer can flexibly customise the final product via various sources.

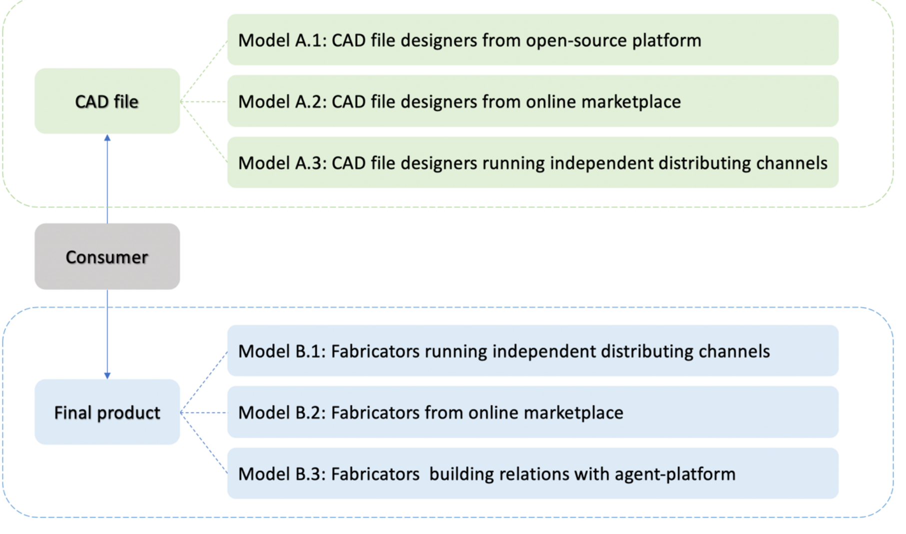

Figure 8: The "separation" business model

The following two subsections analyse the extent to which various business models are different from each other and what these differences mean for product risk.

3.3.1. Model A: Capturing the value created by digital modelling[166]

Under the separation model, a consumer has to firstly contact the CAD file designer. For individuals who are capable of making CAD files, while the emergence of 3D printing removes the scale barrier and offers the potential to capture value in the process of production, it does not mean that everyone can capture the value created by digital designing at zero cost. Although 3D printing promises individuals a chance to gain additional value, it fails to offer them an equal opportunity in respect of accessing the distribution channels. In other words, the democratised nature of digital designing presents huge transaction costs between CAD file makers and consumers. If the cost of developing a distribution channel is so high that it exceeds the value that can be captured by the CAD file makers, they will decide not to enter the market no matter the potential of this cutting-edge technology.

Therefore, it can be seen that the dispersed CAD file makers, as well as consumers who demand customised products, expect an approach that can connect them with each other. Three types of business model have been identified to help the demand and supply sides of CAD files to meet each other. The first two types (Model A.1 and Model A.2) represent the cases where a third-party platform is necessary to facilitate the dissemination of CAD files. In addition, competent CAD file designers may choose a third business model (Model A.3) to reach out to the consumers by developing an independent channel. Model A.3, together with Model A.1 and Model A.2, represent the concrete ways of how a consumer can obtain a CAD file in the current stage. In the next three subsections, a detailed analysis is conducted to show how the three models work in reality.

Model A.1: Acquiring CAD files from an open-source community

Model A.1 is of great importance when CAD file makers are eager to share their digital design online for free. After that, people who are interested in it can download it for the purpose of either transposing it into a physical object or remixing it and then uploading online again.[167]

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[166] The brief introduction of various business models under Model A can be seen in Appendix 1-3.

[167] De Jong, Jeroen PJ, and Erik de Bruijn. "Innovation lessons from 3-D printing." MIT Sloan Management Review 54, no. 2 (2013): 43.

In general, Model A.1 is set up to capture value by offering an "open-source" environment. This phenomenon is no longer perceived as a unique case. Rather, a growing "makers" movement has arisen in support of this trend.[168] Under Model A.1, a mature CAD file can be modified a couple of times by different parties before it is ultimately downloaded. One outstanding feature of Model A.1 is that most of the parties involved in the community, either uploaders or downloaders, are *strangers*. Specifically, for the follow-up CAD file makers who attempt to modify the original digital and for the downloaders who hope to transform the file into a real object, they have limited information on the source of the design, and there is little scope for agreement between the related parties in this model.

Figure 9 shows the complexity of Model A.1. On an open-source online platform, after one party (Party A in the figure) uploads a CAD file, it can be remixed by others (Party B in the figure). Party B's CAD file could further be remixed by other parties (Party C and Party D in the figure). In this thread, if a consumer wishes to download a CAD file from Party E, the digital design in actuality was created by four people (i.e. Party A, Party B, Party C and Party E).

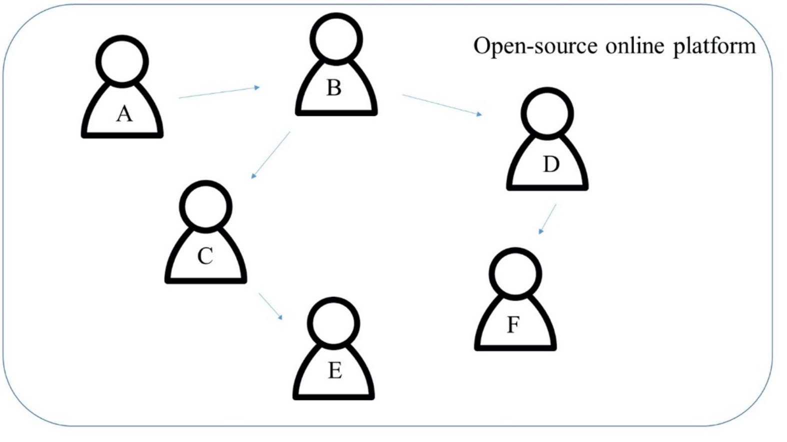

Figure 9: Acquiring a CAD file from an open-source platform (Model A.1)

[168] Gershenfeld, Neil. FAB: THE COMING REVOLUTION ON YOUR DESKTOP--FROM PERSONAL COMPUTERS TO PERSONAL FABRICATION. Basic Books, 2008. Anderson (2014), supra note 155.

To date, a large number of online platforms have been set up to offer cyberspace for digital makers to share their ideas and to enable consumers to benefit from these ideas.[169] Of these websites, *Thingiverse*[170] was the earliest in operation and it is also accessed by the largest audience.

Thingiverse is, in essence, an open-source online platform. It neither runs a business to design CAD files for consumers nor does it own any 3D printers to fabricate the digital designs. Instead, it captures value by reducing the information asymmetry between the supply and demand sides. On *Thingiverse*, anyone, whatever their ability, can open an account to upload their designs. A great variety of digital designs can be accessed from *Thingiverse*. The digital designs are categorised into ten groups on *Thingiverse*.[171] The CAD files that can be downloaded by visitors not only include fashion parts for aesthetic and decorative purposes but they are also comprised of the tools and gadgets that play a functional role in mechanical or household use. For example, if we search "knife" on *Thingiverse*, more than 7,300 results are shown.[172] The most popular CAD file containing a knife is named after "Karambit" (see Figure 10). This knife has been downloaded more than 7,000 times.[173] The Karambit further was remixed by other visitors who re-uploaded a modified version (see Figure 11), which was subsequently remixed again and again by many other new visitors.

[169] Rehnberg, Märtha, and Stefano Ponte. "From smiling to smirking? 3D printing, upgrading and the restructuring of global value chains." Global Networks 18, no. 1 (2018): 57-80.

[170] The official website is: https://www.thingiverse.com/.

[171] They are: 3D printing in general, art, fashion, gadgets, hobby, household, learning, models, tools and toys&games.

[172] The outcome is available at: https://www.thingiverse.com/search?sort=relevant&q=knife&type=things&dwh=665d9ca9066f16a. Visited on October 8th, 2019.

[173] See https://www.thingiverse.com/thing:324433. Visited on October 8th, 2019.

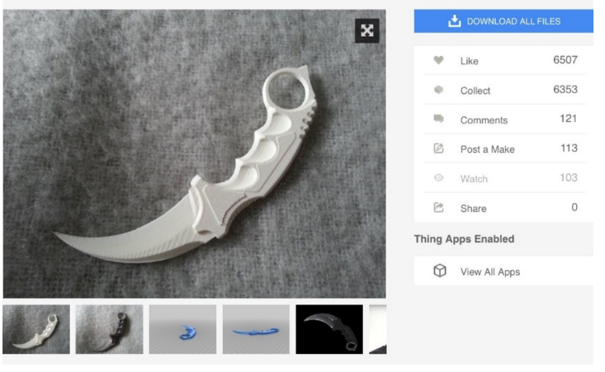

Figure 10: A CAD file of "Karambit" on *Thingiverse* [174]

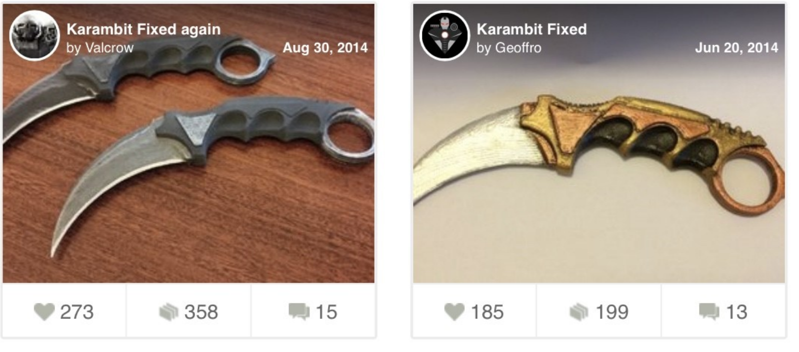

Figure 11: Two remixed CAD file versions of the "Karambit"[175]

Given the open-source nature of Model A.1, a platform such as *Thingiverse* simply operates as a community. After a CAD file is uploaded onto the platform, it is essentially a kind of public

[174] This picture was screenshotted on April 25th, 2019.

[175] This picture was screenshotted on April 25th, 2019.

good.[176] In this sense, any person can take advantage of it without exclusion, which does not affect other visitors to modify and use the CAD file.[177] On *Thingiverse*, as the uploaded CAD files are not substantively reviewed by *the owner or governor of the platform,* CAD files that are of poor quality or that turn out to be unprintable turn out to be ubiquitous online.[178] Unlike traditional production where a product or a design is approved only if it has survived a series of professional experiments, has passed a number of accreditations or has complied with mandatory standards, the quality and performance of a specific digital design originating from an open-source platform are placed online directly without robust specifications. Instead, the quality of a CAD file is improved by the CAD file makers who occasionally take advantage of it.

In the long run, the survival of a CAD file is determined by the market: only the best-functioning and popular ones will survive. Meanwhile, a CAD file that is of inferior quality performing badly will be quickly forgotten on the platform. However, since the removal of a poor CAD file comes at the expense of one or more individuals' negative experiences, this process can be extremely costly and include painful lessons.

Thingiverse is simply an exemplar of Model A.1. In practice, a great number of similar online open-source communities have been established in recent years.[179] To conclude this part, Model A.1 fills the gap effectively by connecting supply and demand. With the assistance of open-source online platforms like *Thingiverse*, value is captured in a way that everyone can make a contribution to it. However, as the involved digital designers under Model A.1 are strangers to each other, information asymmetry turns out to be an insurmountable obstacle among the invloved parties. As a consequence, an agreement deciding on the allocation of risk cannot be reached among the digital designers. As additional digital designers join the chain to remix and improve the CAD file, it becomes even more difficult to do so.

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[176] It is noticed that some limitation on the usage of a CAD file may be posed by its original designer. This case is widely perceived in terms of intellectual property. CAD files within the *Thingiverse* platform are normally constrained by various "CC-agreements".

[177] Weller et al (2015), supra note 9.

[178] Lipson and Kurman (2013), supra note 9, at 217-240.

[179] Other typical cases are *GrabCAD*, *Myminifactory* and so on and so forth.

Model A.2: Third-party platform as a marketplace

The value of Model A.2 is related to linking small demands and the relevant supplies with each other, so that the transaction costs of matching them is reduced.[180] With Model A.2, CAD file makers are able to set up a virtual shop by simply opening an account. Consumers, however, behave as if they are shopping in a real shopping mall. They can browse the webpages and search for the appropriate supplies by customising their preferences. Once the consumers find something that matches their requirements, they can engage with the seller. Unlike Model A.1, in which a number of digital designers who are strangers to each other can keep remixing and improving one CAD file endlessly, in Model A.2 there is only one digital designer. Therefore, the consumer is certain with whom s/he is bargaining. In other words, Model A.2 allows for some information to be disclosed between the parties through the transaction. Therefore, unlike Model A.1, a contractual relationship is formed between the seller and the buyer under Model A.2.

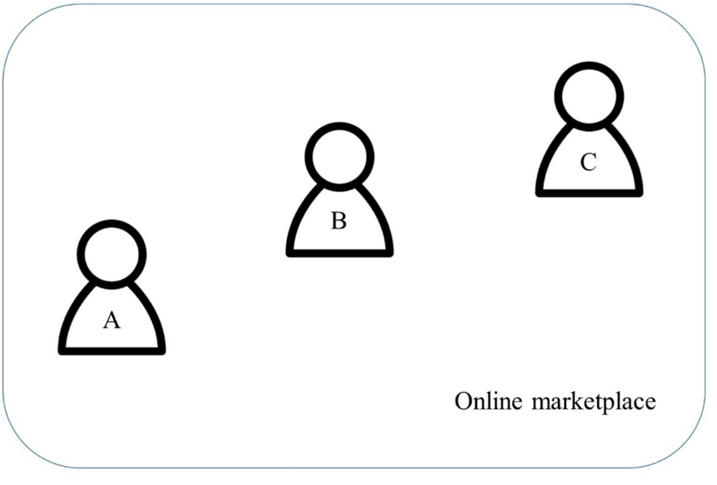

Figure 12: Acquiring a CAD file from an online marketplace (Model A.2)

[180] Holmström, et al. "*Rapid manufacturing in the spare parts supply chain: alternative approaches to capacity deployment*." Journal of Manufacturing Technology Management 21, no. 6 (2010): 687-697.

Figure 12 explains how Model A.2 works. Different CAD file makers (e.g. Party A, Party B and Party C in the figure) run their digital modelling businesses using online marketplaces. Whenever consumers visit the online marketplace, they can make a choice by comparing different CAD file makers.

A typical example of the operations undertaken in Model A.2 is *Pinshape*. Like *Thingiverse*, some of the CAD files on *Pinshape* can be downloaded for free. However, most CAD files on this platform can be downloaded, only if the consumer pays for them. For example, people can purchase a set of CAD files of exoskeleton arms for only $5 from *Pinshape* (see Figure 13). With this transaction, a form of contractual relationship is created between the seller and the buyer, so that there is a chance for them to bargain with each other. Under this scenario, whenever a buyer is harmed, they may claim against the seller on the basis of non-conformity. However, it should be noted that the assessment of non-conformity is determined in the contract, where a seller can embed a disclaimer to avoid bearing the potential liability. In the webpage with exoskeleton arms, the CAD file maker has also placed a disclaimer making it clear that they will not accept any liability for any personal injury resulting from negligent use of the printed product.[181]

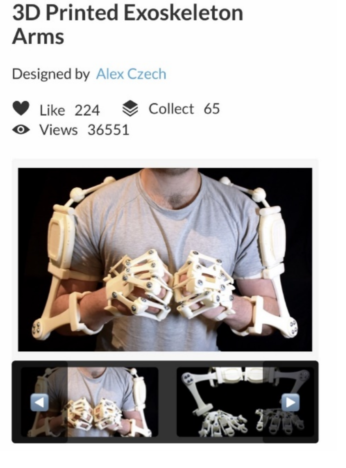

Figure 13: The CAD file of Exoskeleton on *Pinshape*

[181] See https://pinshape.com/items/7257-3d-printed-3d-printed-exoskeleton-arms. Visited on March 2nd 2019.

Model A.3: Obtaining the CAD file in cooperation with the CAD file designer

As explained, Model A.1 and Model A.2 rely on a third-party platform to connect the dispersed demands and supplies in the context of 3D printing. In reality, many CAD file makers choose not to establish their business on third-party platforms.[182] Instead, they prefer to develop an independent channel to satisfy the customised demand from consumers. Figure 14 shows how Model A.3 operates in practice.

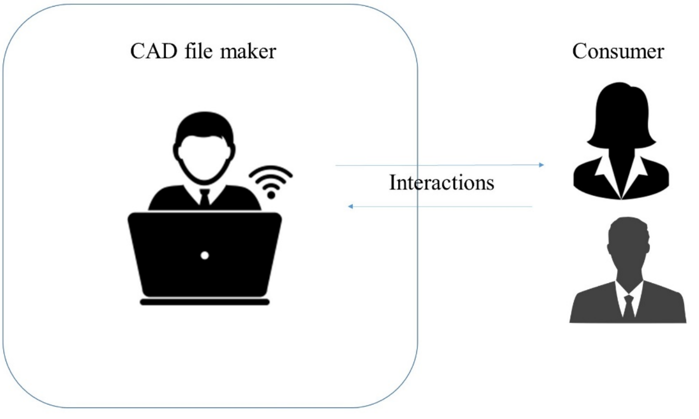

Figure 14: Acquiring a CAD file directly from a CAD file maker (Model A.3)

Compared with Model A.1 and Model A.2, the bargaining between CAD file makers and consumers can be exercised in a more *intensive* way under Model A.3. A typical case used to explain the operation of Model A.3 is *Shapeways*. If a consumer intends to acquire a customised

[182] Many reasons may lead a CAD file maker not to rely on a third-party platform. For example, the CAD file maker may consider that their products may not be easily searched out from a third-party platform and the CAD file maker can afford the cost to establish an independent channel.

CAD file from *Shapeways*, the first thing that they have to do is to consult the expert design team operated by *Shapeways*. The expert will provide the consumer with concrete suggestions on how to achieve the design, and the consumer can provide further feedback within the process of digital modelling.[183] In this regard, the necessary communication between the CAD file maker and the consumer reduces the information asymmetry to a great extent.

Upon comparing Model A.3 with Model A.2, while the CAD file maker and the consumer will finally enter into a contractual relationship within either of the models, the degree of bargaining and the amount of information that is exchanged between parties are significantly different. In brief, Model A.2 focuses more on bridging the gap between supply and demand by offering a marketplace, while Model A.3 is where CAD file makers seek to build relationships with consumers and pay more attention to offering a customised service.

Summaries

To conclude, various models have been established in reality to capture the value associated with CAD files. The analysis explained that these business models are largely different in several aspects regarding risk exposure and risk allocation. These aspects include but are not limited to the capacity of the CAD file designers, the possibility of reaching an agreement between the CAD file designer(s) and the consumer, and the information possessed by the stakeholders to reach an agreement.

Information disclosure may be the lowest under Model A.1, since it is almost impossible to reach an agreement among all of the stakeholders involved in this model, especially when the number of contributors is enormous. In addition, the capacity of the CAD file designers under Model A.1 is relatively low, since the parties that engage in this business model are mostly ordinary individuals, who possess little knowledge of digital designing. Information disclosure is improved to some extent under Model A.2 because the bargaining between a specific CAD file maker and consumer is possible in the virtual marketplace offered by the online platform. Compared with the business

183 For the details on how Shapeways works in terms of digital designing, see: https://design.shapeways.com/?utm_campaign=search_branded&utm_source=google&utm_medium=cpc&utm_content=shapeways&utm_term=shapeways&gclid=Cj0KCQjw2IrmBRCJARIsAJZDdxCb0uvJpbDKl11hDqsUSWcE49J7aubwJXrD5Y4qrM7wAndL2fBSYFYaAhs6EALw_wcB#how-it-works. Visited on June 6th, 201p.

models previously mentioned, information disclosure is intensive under Model A.3, due to the fact that a CAD file is created in collaboration between the CAD file maker and the consumer. At the same time, the capacity of the party who provides the CAD file is expected to be higher in Model A.3 than in Model A.1 and Model A.2, because the participants are mostly medium- or large-sized entities. The distinctions concluded in this part not only have substantial implications for risk exposure but they also have a significant impact on the instruments that should be chosen to deal with product risk.

3.3.2. Model B: Capturing the value created by physical fabrication[184]

Once a CAD file is obtained, the next step is to find a 3D printer. In practice, many parties seek to capture the value by transposing a CAD file into an object.[185] Different business models are thus established. In practice, a CAD file holder generally can rely on three approaches to reach out to printers.

Model B.1: The fabricator establishes an independent platform

Fabricators have different capacities in terms of organising their distributional channels. Like what has been observed in digital designing (i.e. Model A.3), some SMEs, as well as most large-sized professional parties, may invest in operating an independent supply chain. Figure 15 illustrates the operations of Model B.1.

[184] The brief introduction of various business models under Model B can be seen in Appendix 4-6.

[185] Rayna and Striukova (2016), supra note 49.

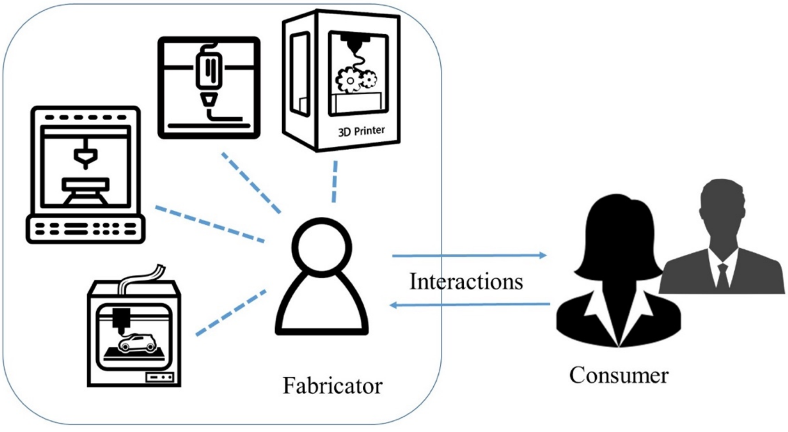

Figure 15: Printing the final object by a professional fabricator (Model B.1)

The typical fabricator that takes advantage of this business model is *Sculpteo*.[186] As a fabricator, *Sculpteo* invests heavily in the purchasing of new 3D printers and methods and in acquiring a variety of materials. In doing so, *Sculpteo* has gained a competitive advantage in the new era by providing an array of solutions rather than focusing on one area of expertise. On its website, a wide range of printing methods and materials can be chosen by consumers. Whenever a fabricator and a consumer reach an agreement, the fabricator will take responsibility for printing the CAD file as well as delivering the final product to the customer.

Model B.2: Seeking the printing service in an online marketplace

Model B.1 applies where a fabricator has the capacity to establish a platform or network in order to meet the demand. In a world where 3D printing substantially open sources the hardware environment, a great number of small fabricators are able to undertake the function of fabrication. In these circumstances, if an online marketplace is established to enable CAD file holders to

[186] Other typical online platforms that adopt this Model are *Ponoko* and *Shapeways*.

identify various suppliers, the value of fabrication in a decentralised context can be captured.[187] This type of business is referred to as the Model B.2, and its operation can be seen in Figure 16 below.

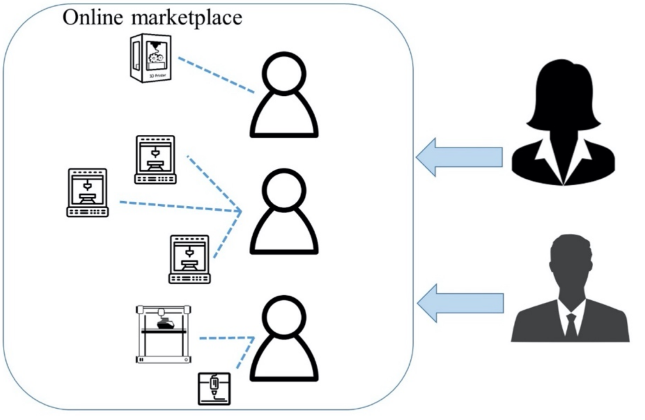

Figure 16: Seeking fabricators from an online marketplace (Model B.2)

The typical example is *Treatstock*,[188] which aims to match the small-volume demand from consumers to the 3D printers that are in the neighbourhood as quickly as possible. A fabricator, either a person or an entity, is able to open an account for free and operate their business in the virtual environment. On its homepage, fabricators can introduce themselves in detail. A consumer not only can compare the printing methods and materials offered by different fabricators in a relatively clear way but they can also consult an interested fabricator about a product solution. Therefore, under Model B.2, the information asymmetry between the fabricators and potential consumers can be reduced.

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[187] von Hippel, Eric A., Susumu Ogawa, and Jeroen PJ de Jong. "The age of the consumer-innovator." MIT Sloan Management Review 53 (2011):1.

[188] Some other platforms that also take Model B.2 are Makexyz and 3Dexperience marketplace. Some fabricators who focus on Model B.1 also perform Model B.2 as an additional business, an example of which is Sculpteo.

What should be noted under Model B.2 is that the online platform only serves as a marketplace. In this regard, platforms like *Treatstock* are simply providing an opportunity for the supply and demand sides to meet in a democratised environment. In this sense, once a fabricator and a consumer are successfully matched, the platform plays no role in their reaching of an agreement. In addition, since anyone who owns a 3D printer can operate their business in an online marketplace, it implies that most of the fabricators are individuals or SMEs.

Model B.3: Platform as an intermediary agent to connect supply with demand

According to the above analysis, either in Model B.1 or in Model B.2, the consumer has to contact the fabricator directly. In these scenarios, it is the consumer that has to evaluate the information disclosed by a fabricator to decide which fabricator can best satisfy his demand. In reality, although platforms hold no 3D printers, by collecting the necessary information that can best match the demands and supplies, they may take the role of being an agent to connect consumers with the supplies that can best satisfy the demands. The contribution of intermediary platforms from this perspective drives to the emergence of Model B.3.

As clarified by Figure 17, the platform does not perform like a neutral marketplace within Model B.3. Instead, it plays a positive role to some extent by representing the consumer to find a suitable fabricator. Therefore, the advantages and disadvantages stemming from an *agency-principal* relationship might be observed in this model. On the one hand, we can expect that information asymmetry to some extent can be reduced. On the other hand, whether or not the agent is diligent in the process of choosing the most suitable fabricator is open to question.

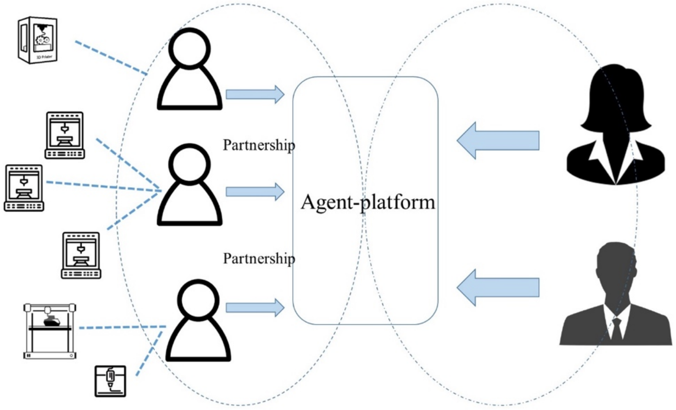

Figure 17: Seeking a fabrication service through an agent-platform (Model B.3)

Here *Craftcloud* is used as an example to explain how Model B.3 works. Whenever the CAD file holders prepare to have their digital model printed, they first have to upload it onto the platform operated by *Craftcloud* and then specify the materials that they would like to use. Within a few minutes, they will get a response from the platform about the manufacturability of the CAD file. If the feedback is positive, a fabricator will be picked by *Craftcloud,* and the process will go into the fabrication phase. The platform as an agent will check the fabricated product before it is sent to the consumer. Lastly, the platform will pack the final product and deliver it to the end-consumer.

Therefore, like Model B.2, the platform in Model B.3 intends to capture value by matching demand and supply. As the platform *Xometry* explains, it was built to solve two problems: one was to help the party from the demand side to find the appropriate source of supply for customisation and the other was to help the parties from the supply side grow their businesses.[189]

Summaries

To conclude, this section distinguished the concrete business models that a fabricator can rely on to capture the value added by the emerging printing activities, which also serve as the approaches

[189] See: https://www.xometry.com/about-us. Visited on June 6th, 2018.

that consumers can undertake and rely on to accomplish the final product after acquiring a CAD file. It is identified that platforms play an important role in matching the supplies and demands. On the one hand, the platform itself can be a direct seller (under Model B.1) to introduce its fabricating business to consumers. On the other hand, the platform may be recognised as a commons (Model B.2 and Model B.3), where fabricators and consumers be matched with each other.

Under Model B.2, the platform offers a commons for fabricators to set up their printing business, which looks like a public good. As the platform sets up no threshold, fabricators, regardless of their capacity, can base their activities on the platform. In this case, the platform simply acts as a marketplace, and it has no contractual relationship with consumers. In comparison, when Model B.3 is adopted, the commons is akin to a kind of "club good" in nature. As the platform in this circumstance contracts with consumers over providing the final product, it will be cautious about choosing its collaborative partners. Because of these extra requirements, many fabricators are thus excluded from the platform.

3.4. Chapter conclusion

This section firstly explains how 3D printing has changed the way of value creation by removing the economies of scale, enabling customization without prohibitive cost, dividing the digital designing from the physical fabrication and increasing the chance for ordinary individuals to engage in production activities. In order to capture the value created by 3D printing, different business models are established. In general, two kinds of business models can be firstly categorized. One is the so-called "one-stop model", which as we analysed shows as having no substantial differences to traditional manufacturing. The other is called the "separation model" where a consumer can only obtain the final product by respectively contacting with digital designers and physical fabricators from different entities. It is this latter type of separation model that is most heavily influenced by the disruptions of 3D printing.

It is analysed in this chapter that, unlike the "one-stop model" in which value-added activities are accomplished within a single entity, under the "separation model", a variety of parties that are strangers to each other are involved in capturing the value. Therefore, one significant consideration of product risk is how these parties are able to be coordinated with each other to ensure the efficient allocation of product risk. In practice, the coordination issue turns to be even more complicated, because the barriers of bargaining over the allocation of risk among relevant parties and the capacity of relevant parties could be in large divergence, given the different ways to capture the value added by CAD file designing or object fabrication. Therefore, it is of great importance to differentiate the business models. The detailed divergence among various business models regarding the separation model is summarized in Table 5.

The variation in business models results in different levels of bargaining, and the information that is perceived by the relevant parties can also be different. Under the business models in which a CAD file maker or fabricator can establish a platform on its own (i.e. Model A.3 and Model B.1), the intermediaries are removed. For other business models, due to the fact that parties would not meet with each other, they need an intermediary to connect them with each other. As a result, the level of bargaining varies due to the divergent roles of the platform. Table 5 reflects this divergence. Firstly, in the case where supply and demand are matched with each other in a marketplace (i.e. Model A.2 and Model B.2), the level of bargaining is low. This is because the information obtained by the consumer is highly dependent on the description given by the CAD file maker or fabricator. Such information could be rather limited and misleading, especially when few signals are offered by the CAD file maker or the fabricator who may have little knowledge about the safety of their output. Secondly, the sufficiency of bargaining could be even lower in a business model that is directed by an open-source environment (Model A.1). In this context, two factors determine the difficulty of bargaining. One is that the uploaders and downloaders are strangers, which implies that normally no information is exchanged between them. For the other, as a digital design is modified by a number of parties, it is impossible for the downloader to bargain with each of them. Finally, the platform itself may play a key role in terms of bargaining. Under Model B.3, the online platform serves as an agent to determine which fabricator can offer the printing service. Therefore, information is not conveyed from the fabricator to the consumer through bargaining. Rather, information is offered based on the trust in the platform.

Besides the divergence in information, people can also witness a great difference in the capacity of the actors among different business models. As Table 5 shows, ordinary individuals (Model A.1, Model A.2 and Model B.2) have contributed the most to capture the value created by adopting 3D printing. However, compared to traditional mass producers and SMEs (Model A.3, Model B.1 and Model B.3), ordinary people are expected to be less capable of dealing with product risk.

Therefore, the discussion in this chapter shows that risk-allocation could be extremely complicated, especially when the divergence of the business models established for capturing the value of digital designing and physical fabrication is taken into account.

Table 5: A summary of the business models in the context of 3D printing

Business Model	Business model	Capacity of designers/fabricators	Is a third-party platform necessary	The role of the third-party platform	Level of bargaining	Contractual relationship	Typical operators
Separation Model	Model A.1 (digital designing)	Individuals	Yes	Open-source	Very low	-	*Thingiverse*
	Model A.2 (digital designing)	Individuals and small entities	Yes	Marketplace	Low	CAD file maker – consumer	*Pinshape*
	Model A.3 (digital designing)	SMEs and large entities	No	-	High	CAD file maker – consumer	*Shapeways Voodoo*
	Model B.1 (physical fabrication)	SMEs and large entities	No	-	High	Fabricator – consumer	*Sculpteo Stratasys Direct SD3D*
	Model B.2 (physical fabrication)	Individuals and small entities	Yes	Marketplace	Low	Fabricator – consumer	*Treatstock Makexyz 3Dexperience*
	Model B.3 (physical fabrication)	SMEs	Yes	Agent	Depending on the agent	Fabricator – platform – consumer	*3D Hubs Craftcloud Xometry*
One-stop Model		SMEs and large entities	No	-	High	Producer – consumer	*Invisalign*

Conclusions

The discussion up to this point has shown that 3D printing is significantly different from traditional production. While it can by no means replace the dominance of traditional manufacturing, the fact that it adds great value to the sector of production provides people with another option to match their demands with a wide range of supplies. However, it must be noted that risks meanwhile emerge along within and alongside the process of value creation.

As digital designing is separate from physical fabrication, a consumer is able to acquire a CAD file from one source and then have it printed out by another one, which implies that CAD file designers and final fabricators are usually strangers to each other. Therefore, risk allocation under such "separation models" is significantly different from the pattern of traditional manufacturing, since the coordination of risk allocation is beyond a single entity.

This part concludes with the potential risks that are generated when 3D printing is linked with production, and especially indicates the extent to which various separation models are different in terms of risk exposure.

Product risk within the digital modelling and fabrication process

Firstly, product risk is generated because digital modelling and physical fabrication can both have an impact on product safety.

According to the technical characteristics of 3D printing, *digital modelling* is decoupled from physical fabrication.[190] The fact that the quality of the CAD file directly determines the function and performance of the final product implies that digital design is crucially important in the context of 3D printing compared to traditional manufacturing.[191] A code can instruct further operations of the 3D printer, and a CAD file cannot be guaranteed to be completely correct.[192] The substantive

[190] See the discussion in Chapter 1.

[191] See the discussion in Section 1.2, Section 3.1.2 and Section 3.2.2.

[192] Choi, Bryan H. "Crashworthy code." Wash. L. Rev. 94 (2019): 39, at 44.

risks that arise from the process of obtaining a CAD file indicate that the relevant parties, which have the potential to contribute to those risks, should also be offered an incentive to behave appropriately.[193] Apart from the risks generated in the process of digital modelling, activities undertaken by fabricators can also pose risks. Unlike traditional manufacturing where manufacturers play a dominant role in determining the quality of the product, fabricators with 3D printing follow the instructions in the CAD files. While the impact is not a determinant, the activities undertaken by the fabricators, which relate to setting up the printing environment and post-printing process, may influence the performance of the final product as well. Therefore, particular instruments should also be offered proportionately to the risk caused by fabricators.

To summarise, the way of production adopted by 3D printing implies that fabricators may no longer be the party that can reduce product risk at the cheapest cost. Instead, the CAD file designer may play an increasingly important role in the context of 3D printing in terms of determining the safety of the final product. In this case, legal instruments may also need to be altered to target CAD file designers by providing them with additional incentives to reduce risk.

Product risk pertaining to information asymmetry

Apart from the risk generated in the realm of digital modelling and the one added by new entrants in fabrication, product risk can also be less controllable because the information is asymmetrically perceived by different parties.

Under traditional production, production activities are commonly accomplished within one entity. Where a number of entities are responsible for providing components, distribution and retailing, a linear supply chain will emerge to connect all of the relevant parties and this chain will also act as a channel to deliver information. In addition, a variety of signals, ranging from reputation to compliance with standards, are also used by consumers to assess production. Therefore, multiple instruments exist to reduce the information asymmetry between the parties along the supply chain and between the sellers and consumers.[194]

[193] Geistfeld, Mark. "Negliegence, Compensation, and the Coherence of Tort Law." Geo. Lj 91 (2002): 585.

[194] See the discussion under Section 3.1.1.

In comparison with traditional production, under the "separation models" of 3D printing, the parties who engage in digital modelling and physical fabrication are strangers to each other. In this regard, a fabricator who establishes their business under Model B may not correctly estimate the potential risk of a CAD file that is chosen by the consumer from designers under Model A. Similarly, a digital designer may also have difficulty in estimating whether its CAD file would be finally printed out by a competent fabricator or not. As a result, besides the information offered by consumers, the CAD file designer and fabricator have little chance to coordinate with each other for the allocation of risk. If one specific party, either the CAD file designer or the fabricator, is designated as the party to bear the risk, s/he at should gain the safety information from other parties who pose risks as well. Otherwise, even if this particular party is deemed liable, s/he cannot include the cost that posed by other parties into the full price, which will still mislead the choice of consumers.

Assuming that consumers hold perfect information and can correctly decide the risk associated with designers and fabricators proportionately, the coordination issue should not be a problem because the consumer will always know which party generates the lowest cost compared to the others. In the long run, as transactions in the market will reflect the choice of consumers, those risky parties will be pushed out of the market. However, this is not the case in the context of 3D printing, unless there are reliable instruments to signal credible information to consumers.

According to the analysis in Part I, the severity of information asymmetry differs among the different business models adopted by actors for the purpose of capturing the value created in digital designing and physical fabrication.[195] It can be imagined that, compared with the situation in which a consumer obtains a CAD file from a professional SMEs (i.e. under Model A.3) and then ask a professional fabricator under Model B.1 to print it out, it will take a greater effort to evaluate the risk in another case, where a consumer obtains a CAD file from an open-source community (i.e under Model A.1) and then find an individual fabricator (under Model B.2) to print it out.

[195] See the summary in Table 5.

Product risk generated by individuals and SMEs

Thirdly, the product risk posed with 3D printing shows new features when we differentiate the parties that engage in relevant activities. One significant disruption caused by 3D printing is that production is no longer constrained by economies of scale.[196] With 3D printing, value is mainly created and captured by the parties, provided that they are able to satisfy a wide scope of demands, especially the ones on the long-tail. Therefore, not only are traditional mass producers involved in substantive activities but also SMEs and even ordinary individuals who are non-professionals.[197]

The increasing engagement of individuals and SMEs also raises concerns about the risk-spreading issue. Compared with traditional mass producers, individual producers and SMEs are less capable of bearing the risk. Therefore, we must be very careful when it comes to allocating product risk under different business models in the context of 3D printing.

Having observed the divergence of the different business models and having come to understand how this divergence could result in risk at different levels, in Part II the focus shifts to exploring the efficiency of various instruments when they are employed to reduce accidents and to help shift risk in different business models.

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[196] See the discussion in Section 3.2.2.

[197] See the discussion in Section 3.2.2.

PART II

DETERRENCE AND RISK-SHIFTING IN THE CONTEXT OF 3D PRINTING THROUGH THE LENS OF CONTRACTUAL RELATIONS

Introduction

The discussion in Part I explained that adopting 3D printing in the sector of production not only creates enormous value but also poses risks to users. Law and economics theory indicates that we need to provide relevant parties with the incentive to optimise their activities. In other words, we expect to employ specific instruments to lead them to behave in such a way that social welfare can be maximised. On the one hand, the related parties should be incentivised to take the optimal level of care and activity. On the other hand, the risk-averse parties should not bear the risk. Against this background, the main interest of Part II is to explore the extent to which contractual relationships and related instrumental interventions can result in the optimality expected by law and economics.

The analysis in this part proceeds as follows. The discussion in Chapter 4 firstly reveals that, given some assumptions, the socially optimal outcome can be achieved through bargaining. Taking this perfect situation, the discussion in the second part of Chapter 4 explores the extent to which this efficient outcome can be distorted in reality, especially in the scenarios where transaction costs and information problems cannot be ignored. Chapter 5 applies this analytical framework in the context of 3D printing, and sheds light on its implications for different business models.

Chapter 4. Bargaining over the Product Risk: Theory and Practice

In the sector of production, while a product can create massive value for both producers and users, it inevitably poses risks to some extent. The fact that production not only creates value but also externalises risks implies that production should not be prohibited entirely. Instead, we need to encourage parties to adopt measures to optimise the behaviour of the involved parties so as to maximise the social welfare.

The law and economics theory indicates that if the ownership of entitlement is clearly defined and no transaction cost is present, irrespective of which party is allocated the entitlement, the party which has the highest value will ultimately hold this entitlement.[198] This theory also applies to externalities. If the law has explicitly decided that a party has the right to generate externalities or instead that a party is exempted from being harmed, given no transaction cost, the party which values the entitlement at the highest price will always, in the end, attempt to possess the entitlement.[199] In this regard, no legal intervention is needed. The role of the courts is simply to confirm and enforce the contractual allocation of product risk.[200] After a court made an action toward or a law defined the allocation of damage, the affected parties would always renegotiate to find a way or another to maximise their joint benefit.[201]

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[198] See Coase (1960), supra note 8; Ogus, Anthony I. Costs and Cautionary Tales: Economic insights for the law. Bloomsbury Publishing, 2006, at 27.

[199] McKean, Roland N. "Products Liability: Implications of Some Changing Property Rights." The Quarterly Journal of Economics 84, no. 4 (1970): 611-26.

[200] Coase, Ronald H. "The Federal Communications Commission." The Journal of Law and Economics 2 (1959): 1-40; see also Geistfeld, M. "Product liability." in Michael Faure (ed.) ENCYCLOPEDIA OF TORT LAW AND ECONOMICS, Edward Elgar, (2009).287-340, at 288.

[201] Priest, George L. THE RISE OF LAW AND ECONOMICS: AN INTELLECTUAL HISTORY. Routledge, 2020, at 43.

According to the literature, transaction cost was initially invented to indicate the costs of using a price mechanism.[202] Transaction cost can be divided into three categories: the cost of discovering what the price is, the cost of negotiating and concluding a contract, and the cost of enforcing the agreed contract.[203] Further, the importance of information cost is highlighted in the literature.[204] A powerful statement regarding this delineation is that even when the transaction costs are assumed to be zero, uncertainties can still be found leading stakeholders to make inefficient decisions.[205] The discussion in this research follows this approach: transaction cost is defined as any cost that deters relevant parties from bargaining directly over the allocation of risk, while information cost (or information problems) refers to the situation where contractual parties hold imperfect information as a result of misperception or uncertainty. Both of these issues will prevent parties from reaching a deal smoothly.

Thus, the content of this chapter can be divided into two parts. Firstly, in Section 4.1, I will delve in-depth into the situation where transaction costs and information problems are assumed to be non-existent. In this perfect world, law and economics theory concludes that legal intervention is unnecessary since personal bargaining can result in efficiency. Secondly, in Section 4.2, the critical assumption on zero transaction cost and the absence of an information problem is relaxed, the aim of which is to disclose the extent to which contracting for product risk could result in a distorted outcome in terms of efficiency and to imply the necessity for further instrumental intervention.

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[202] Coase, R. H. "The Institutional Structure of Production." The American Economic Review 82, no. 4 (1992): 713-19.

[203] See Allen, D. "Transaction costs." in Boudewijn Bouckaert and Gerrit De Geest (eds) ENCYCLOPEDIA OF LAW AND ECONOMICS, 893-926, at 895.

[204] Literature even articulates that all the different sources of transaction costs can be regarded as the problem of a lack of information, meaning that transaction cost essentially is information cost. Dahlman, Carl J. "The Problem of Externality." The Journal of Law & Economics 22, no. 1 (1979): 141-62.

[205] See Barzel, Yoram. "Some fallacies in the interpretation of information costs." The Journal of Law and Economics 20, no. 2 (1977): 291-307. Regarding this issue, McKean clearly explains that "if we are to consider products-liability issues in a world of zero transaction costs, however (and in my view it is useful to start that way), that world cannot mean zero information costs in the sense of complete certainty about everything; for in those circumstances there would be no defects, carelessness, chance, accidents, or questions of liability." See supra note 199, at 617-618.

4.1. Contracting over product risk in the perfect world

The analysis in this section is based on the early literature, which makes several crucial *assumptions*.[206] First and foremost, there is *no transaction cost* between the producer and the consumer, so they can reach an agreement smoothly and the product can be transferred from the former to the latter directly. Secondly, the entitlement regarding externality is completely *defined* before a producer and a consumer bargain with each other. Thirdly, all contractual parties hold *perfect information*, which means that the parties are able to find the socially optimal outcome and that no information asymmetry exists between them. With perfect information, all the incidents that increase the cost borne by a party can be precisely observed and factored into the party's full price. Fourthly, the market setting is perfectly *competitive*. Fifthly, contractual parties are *risk-neutral*, which means that social welfare will not be diminished due to risk-aversion.

Different circumstances have been set up by law and economic scholars, the purpose of which is to identify the socially optimal outcome in various scenarios and consider how people can bargain over product risk efficiently. This section will briefly go back to these classic discussions starting from the simplest case of unilateral precaution, where deterrence is only correlated with the precaution taken by the producer. Then, the analysis moves to a more complicated case where the precaution of the consumer plays a role in reducing product risk. Finally, the case in which the underlying *activities* from both sides have an impact on deterrence efficiency is considered. The end of this section concludes that in circumstances where the assumptions are satisfied, the party which values the entitlement at the highest price will ultimately possess it; this indicates that resources can be efficiently allocated through contractual relationship. More importantly, concerning deterrence, it is also revealed that the parties which internalise the costs will be incentivised to optimise their activities so that social welfare is maximised.

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[206] See Coase (1960), supra note 8; Oi, Walter Y. "The economics of product safety." Bell Journal of Economics 4, no. 1 (1973): 3-28; Rubinstein, Ariel. "Perfect equilibrium in a bargaining model." Econometrica: Journal of the Econometric Society (1982): 97-109; Priest, George L. "Can absolute manufacturer liability be defended." Yale J. on Reg. 9 (1992): 237, at 252.

4.1.1. Bargaining over product risk: where precaution can only be taken by the producer

For simplicity, assume that an accident is only correlated with the precaution taken by a producer, which directly sells the product to a consumer, who is also the victim. In this case, neither the quantity of product nor the frequency of activity relating to the product is presumed to influence the socially optimal outcome. Also, assume that the externalities generated by an accident are not inalienable and that neither transaction cost nor information asymmetries are present between the producer and the consumer. In this scenario, optimal deterrence will be achieved if the accident cost is minimised by incentivising the producer to optimise its precaution. Relevant variables that affect the level of accident cost are listed below:

c: the production cost of a unit of product

x: the cost of prevention taken by the producer

p(x): the probability of an accident given the care level of the producer

D: the damage caused by the product

p(x)D: the expected harm given the care level of the producer

Having delineated the correlated factors, the full price (P) of a product thus can be determined as:

$$c + x + p(x)D$$

If a consumer is initially allocated the entitlement of not being harmed, a producer has to make an offer to the consumer in order to transfer the product. The offer consists of three kinds of cost: the production cost, the cost of precaution, and the cost of the expected harm. In this sense, the producer is bargaining with the consumer by way of revealing the full price of the product. Given that the consumer holds perfect information, s/he can accurately decide at which level the care taken by the producer can result in the lowest possible full price. In other words, the consumer can precisely identify the optimal level of care that should be taken by the producer. If a producer is found not to be taking the optimal precaution, the consumer can recognise the corresponding variation in the full price.[207] As a result, the consumer will turn to another producer for a lower full price.[208] In a competitive market, this prospect can be achieved.[209] Taking the consumer's ability to assess the full price into consideration, the producer will be induced to optimise his level of precaution (x*).

Now let us consider the opposite situation that the producer is initially entitled to the right to generate externalities in the course of production. In this sense, the market price is the sum of the production cost and precaution cost. However, the consumer who is assumed to hold perfect information will make his/her decision based on the full price that also includes the expected harm given the precaution of the producer.[210] As the consumer is presumed to hold perfect information, s/he can accurately assess at which level of precaution the least full price results. Specifically, if a market price is set lower than c + x*, then the consumer understands that the producer is not investing sufficient effort to take precautions; if the market price is set higher than c + x*, the consumer can recognise that the producer invests more in precautions than is necessary.[211] All these deviations remind the consumer that s/he can find an alternative to make the deal. As a result, the producer will be incentivised to optimise its precaution (x*).

To summarise the analysis in this subsection, in the case that only the producer can reduce product risk, irrespective of who is initially allocated the entitlement, given that all assumptions are satisfied, the producer and the consumer will only reach an agreement when the producer takes the optimal level of care. In reality, the case that only producers can take precautionary efforts to reduce product risk is very rare. In most cases, consumers can also reduce product risks through their precautionary efforts. This latter occasion will be explained in the next subsection.

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[207] If the market price is set lower than the minimum of the full price, the consumer is presumed to understand that while he pays a lower price at the time of transaction, after s/he transfers the entitlement of not being harmed by externality, he has to take risk to bear a higher amount of expected harm. In another case, if the market price is set higher than the minimum of the full price, the consumer will understand that the producer invests too much precaution than optimality, meaning that an extra of one unit precaution decreases the expected harm that being less than a unit.

[208] See McKean (1970), supra note 199, at 617-618.

[209] In contrast, in a less competitive market, as consumers have limited access to alternative producers, the incumbent producers turn to be less responsive to consumers. See McKean (1970), supra note 199, at 619.

[210] In this context, as McKean articulated, "purchasers of products would hire producers to include safety features." See See McKean (1970), supra note 199, at 617.

[211] In this context, according to the wording of McKean, purchasers would "hire themselves to be careful as long as these actions paid." See ibid.

4.1.2. Bargaining over product risk: where precaution can also be taken by the consumer

The analysis so far indicates that in a scenario where only the precaution of the producer has an impact on product safety, efficient deterrence can be achieved through bargaining given that neither transaction cost nor information problems are present. In this section, the circumstances in which the precaution of the consumer can also influence product safety are discussed. An additional variable of the precaution taken by the consumer is therefore included in our analysis:

y: the cost of precaution taken by the consumer

Two instances are distinguished when it comes to the different roles played by the precaution of a consumer in an accident.

Bilateral precaution

Bilateral precaution refers to the case where both producers and consumers have to take some measures in order to avoid a single risk.[212] Compared with the setup of unilateral precaution, bilateral precaution seems to more closely resemble the context of production. We determine the full price as:

$$P = c + x + y + p(x,y)D$$

Firstly, suppose that the consumer is initially entitled to the right not to be harmed by the externalities generated by the product. In order to transfer the product to the consumer, a producer has to include the accident cost in the offer, which is set as $c + x + y + p(x)D$. Given that consumers hold perfect information, the producer attempts to minimise this offer by optimising its level of care. In this situation, investing lower or higher precaution will simply increase the sum of the

[212] Shavell, S. (2009). ECONOMIC ANALYSIS OF ACCIDENT LAW. Harvard University Press, at 9-10.

offer, which will place this producer at a less competitive position in the market. The consumer then will make his/her decision by comparing his/her utility with the full price. As the producer promises to take the optimal care level, the full price accessed by the consumer is $c + x^* + y + p(x^*, y)D$. The consumer will also be incentivised to optimise his/her precautions, because otherwise it will be accurately observed by the producer, who will then decide to deal with another consumer with lower risk. As a result, optimal deterrence from both sides can be achieved in this case.

If the producer is initially entitled to the right to generate externalities in production, optimal deterrence can also be achieved through bargaining, given that all assumptions are satisfied. In this case, if a consumer is interested in a product, s/he has to compare the utility of the product with its full price, which is $c + x + y + p(x, y)D$. The consumer would like to purchase the product at the lowest price. As a result, on the one hand, the producer will attempt to minimise the cost relating to his behaviour (i.e., $c + x^* + p(x^*)D$) because, otherwise, the competitive market will lead the consumer to another producer that has optimised the level of care; on the other hand, the consumer is induced to minimise the cost generated by his/her behaviour (i.e., $y^* + p(y^*)D$).

In summary, no matter how the entitlement is initially decided, in the scenario that both producers and consumers can take precautions to reduce accidents, given the preliminary assumptions hold, these parties ultimately will be incentivised to optimize their level of care. Product risk thus can be efficiently allocated through contractual relationship.

Alternative precaution

Alternative precaution is an extreme case, which in theory should be distinguished from bilateral precaution. As we identified, bilateral precaution requires both the injurer and victim to take care, so that a socially optimal outcome can be achieved. In comparison, while either party can take alternative precautions, the accident cost resulting from the precaution of a single party is lower than the one that results from any kind of cooperation by the two parties. In other words, the socially optimal outcome can be achieved simply by asking one party to take precautions rather by requiring both parties to take precautions.[213] Having both parties take precautions turns out to be a waste in this situation.[214]

In theory, alternative precautions may be observed in the sector of production. Suppose that the safety of a product is related to five kinds of risk (i.e., Risk A, Risk B, Risk C, Risk D and Risk E). In many cases, the socially optimal outcome is achieved by having producers and consumers each take part of the overall risk. For instance, the socially optimal outcome may be achieved by allocating Risk A, Risk B and Risk C to the producer and allocating Risk D and Risk E to consumers. According to a previous study, this efficient result can be achieved through bargaining. However, there is a possibility that the producer can avoid all five kinds of risk at the least cost. In this case, while the accident can be avoided by both parties, it ends up with an efficient outcome by having only one party take precautions. If contractual parties can bargain with each other with perfect information, which means that one party is clearly revealed to avoid the accident at the cheapest cost in every possibility, the optimal deterrence will be precisely allocated to the contractual parties.

However, it should be noted that in the sector of production, alternative precaution is rarely observed. It is hard to imagine a case where the producer *with every possible risk* can avoid the accident at a cheaper cost than consumers. Once the product is transferred to the consumer, risk turns out to be less controllable by the producer. In this regard, as long as a product leaves the hand of the producer, it could be cheaper for the consumer or other following parties rather than the producer to reduce the risks. This also explains why these following parties should also be provided with an incentive to behave appropriately.

4.1.3. Bargaining over product risk: where activity level also matters

Precautionary measures are important ways of reducing accidents, but they are not the only ways. Product risk is also related to the level of activities taken by relevant parties. In law and economics literature, scholars have different understandings of meaning of activity level. The majority of

[213] Dari-Mattiacci, Giuseppe. "Tort Law and Economics." in Hatzis Aritides (ed.) ECONOMIC ANALYSIS OF LAW: A EUROPEAN PERSPECTIVE, Edward Elgar (2003).

[214] Shavell (2009), supra note 212, at 16-17.

scholars agree that the level of activity is irrelevant to precaution but refers to the quantity or intensity of an activity.[215] Two assumptions are made when it comes to the level of activity: an increase in activity will add an extra accident cost (the sum of the precaution cost and expected harm); and, an increase in activity will increase the utility of a party.[216]

In the context of production, the meaning of the activity level can be explained in two ways based on the distinction between different types of product. On the one hand, for *services* and *non-durable products*, the activity level can be interpreted as the quantities that consumers purchase from a producer.[217] In this sense, the activity level of the producer and the activity level of the consumer are regarded as the same variable.[218] On the other hand, for *durable* products, the activity level can be interpreted as the intensity of activities taken by the parties. For consumers, it means how intensively they use a particular product. For a producer, it means how often it would like to apply new features (e.g. designs and functions) to the product.[219] The following analysis discusses the deterrence effect for each of these circumstances.

The quantity of the product as the activity level

For services and non-durable products, the activity level means the quantity of a particular product purchased by a consumer. As the utilities gained by contractual parties are respected, additional variables regarding them are added to the model:

U_P: the utility the producer gains from the activity

U_C: the utility the consumer gains from the activity

q: the quantity of products that are sold to consumers

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[215] Shavell (2009), supra note 212, at 21. See also Polinsky, A. Mitchell. "Strict Liability vs. Negligence in a Market Setting." The American Economic Review 70, no. 2 (1980): 363-67.

[216] Polinsky (1980), ibid.

[217] Shavell, Steven. "Strict Liability versus Negligence." The Journal of Legal Studies 9, no. 1 (1980): 1-25.

[218] Shavell (1980), ibid.

[219] Shavell (1980), ibid.

The scenario that a consumer is initially allocated the entitlement of not being harmed is considered first. Under this circumstance, the producer has to make an offer, including the potential accident cost related to its behaviour (i.e., c + x + y + p(x)D) to the consumer.[220] This offer is also the market price that is set for the product. Since the consumer can precisely perceive this full price, the producer will be incentivised to take the optimal level of care (x*).[221] If the producer fails to optimise its care level, a higher accident cost will be included in the full price. In this scenario, the consumer would not wish to accept the offer and will turn to other producers that optimise the level of care.[222] Therefore, the producer will be incentivised to take optimal precautions. It is also noted that the full price not only contains the variable related to the level of care taken by the producer, but it is also related to the level of care taken by the consumer.[223] Therefore, in order to minimise the value of the full cost, the consumer will be induced to optimise his/her level of care, because otherwise the additional cost would be well observed by the producer which would finally be included the market price. After precisely observing the full price of a product, the next core issue for consumers is how much of the product they should buy. In terms of the total consumption in society, any consumer who values the utility of the product higher than the full price (i.e., $U_C >$ c + y + x + p(x,y)D) will choose to purchase the product. Consumption will continue until the last consumer makes such an evaluation. In this situation, the amount of the total utility (i.e. $U_C(q)$) less the total full price (i.e. q[c + y + x + p(x,y)D]) is maximised. In another case, where a single consumer purchases a kind of product repeatedly, s/he will attempt to end his/her activity when the utilities of the product are maximised. Therefore, even if the quantity of the product has an

[220] It is noted that in order to make an appropriate offer, the producer has to correctly observe the probability of the accident not only given his care level but also more importantly, given the precaution taken by the consumer.

[221] A consumer holds perfect information here means that he is not only able to precisely understand the care level taken by the producer, but also he is able to understand the probability of accident given the precaution taken by both parties (the consumer can even distinguish the proportion that (p(x)D) and (p(y)D) respectively result in the probability). In other words, if the consumer misperceives producer's care level or the probability of harm given their precautions, he would count the wrong amount of the offered and result in the wrong comparison between utility and the full price.

[222] Shavell (2009), supra note 212, at 52.

[223] To explain it, the size of the full price is determined by the care level by the consumer (y) as well as by the expected damage given the care level of the consumer (p(x,y)D).

impact on social welfare, the socially optimal quantity of products will, in the end, be chosen by the contractual parties through bargaining.

The same result can be observed in the scenario when a producer is entitled to the right to cause externalities in the course of production. In this case, in order to utilise the product, the consumer has to undertake the cost of production as well as the accident cost that is related to the externalities generated by the producer. As observed before, given that consumers hold perfect information, producers will be incentivised to take the optimal level of care (x*) since any deviation would result in a loss of consumers. Then, the full price is: $c + y + x^* + p(x^*,y)D$. Understanding that the precaution taken by them will also influence the full price, consumers thus will be incentivised to optimise their level of care (y*). Then, the question turns to how much of the product will be consumed. The answer to this question goes back to the comparison between the total utilities that have been gained by consumers and the full price that has been paid by them. The maximum of social welfare is achieved at the last point, where an increase in activity results in greater utilities than costs.[224]

To summarise, in a bilateral case where socially optimal deterrence is not only influenced by the precaution taken by the producer and consumers but is also correlated with the quantities purchased by consumers and where there is zero transaction cost and perfect information, bargaining enables parties to take optimal precautions as well as to consume the socially optimal quantity. This conclusion applies no matter who is initially entitled or what externalities are generated by the use of the product.

Behaviour intensity as the activity level

In addition to the case where the quantity of production influences social welfare, the intensity of activity is also considered to have a substantial impact on social welfare. Additional variables are as follows:

w: the intensity of the activity of the producer

z: the intensity of the activity of the consumer

[224] That is $\Delta U_C(q) > \Delta q[c + x + y + p(x,y)D]$.

Firstly, let us consider the case where the consumer is initially entitled to the right to not being harmed by the product. In this scenario, in order to conclude a contract with the consumer, the producer has to make an offer that covers the related costs. The composition of the costs includes not only the production cost but also the accident cost in terms of precaution as well as the intensity of activities. The offer from the producer is therefore: $c + wx + yz + wzp(x,y)D$. Given perfect information, the consumer can precisely assess the level of care taken by the producer as well as the probability of an accident associated with the producer's level of care and the activity level. In this regard, the producer will be induced to optimise its level of care (x^*) as well as the activity level (w^*)[225]. If it fails to do so, the consumer can precisely identify the extent to which this deviation will increase the full price, and the consumer will turn to other producers that adopt an optimal care level and activity level. Since the producer also fully understand the optimal behaviour of the consumer, s/he will also include the accident cost relating to y^* and z^* into the full price. Therefore, the full price that consumers perceive when they receive the offer from the producer is: $c + w^*x^* + zy + w^*zp(x^*,y)D$. The consumer is incentivised to optimise his/her level of care (y^*) and activity level (z^*) as well[226], because the accident cost beyond y^* and z^* is not included into the market price and has to be borne by the consumer him/herself. Therefore, whenever the intensity of producers and consumers influences social welfare, socially optimal deterrence can be achieved through bargaining given that the entitlement of not being harmed is initially allocated to the consumer and that neither transaction cost nor information problems are present.

Then, we consider the context where the producer is initially entitled to the right to generate externalities in the course of production. In this scenario, in order to transfer the product from the producer to him/her, apart from the production cost, the consumer also has to include the accident costs that are generated by both parties. Therefore, the consumer will make a decision based on the full price of the product, which is: $c + wx + zy + wzp(x,y)D$. Given perfect information, when

[225] The producer will decide his optimal level of precaution by maximizing the difference value between the total utilities he gains by conducting relevant activities and the total costs that he should bear. S/he will stop his activity at the last point where his/her activity creates more utility than the costs (i.e., the point where $\Delta U_P(w) > \Delta[wx + wp(x)D]$)

[226] The consumer will decide his optimal level of precaution by maximizing the difference value between the total utilities that he gains from relevant activities and the total costs that he should bear. He will stop his activity at the last point where his activity creates more utility than the costs (i.e., the point where $\Delta U_C(z) > \Delta[wx + zy + wzp(x)D]$)

the consumer can accurately perceive the precaution invested by the producer and can precisely understand the extent to which the producer's activity level will have an impact on the expected harm, the consumer can accurately distinguish the cost generated by the producer ($c + w^*x^* + w^*p(x^*)D$) from the full price; thus, the cost generated by the producer is the highest offer a consumer would wish to make. If the producer asks for a bargain higher than this amount, the consumer will not accept. Instead, the consumer will turn to other producers until one of them accepts this offer. In these circumstances, the producer in a competitive market will be incentivised to optimise its care level (x^*) as well as activity level (w^*) so as to achieve the least cost. In addition, as the full price is also correlated with the behaviours of consumers, in order to minimise the full price, consumers will be incentivised to optimise their level of care (y^*) and level of activity (z^*). To summarise, just as when consumers are initially entitled to the right of not being harmed by the externalities, given that neither transaction cost nor information problems are present, the socially optimal outcome also results when the entitlement is initially allocated to the producer.

4.1.4. Summary

The discussion in this chapter implies that if the entitlement with regard to externality (i.e., $wx + yz + wzp(x,y)D$ in a bilateral accident) is clearly defined, that there is no transaction cost in reaching an agreement, and that the parties hold perfect information, these parties can resolve the externality problem efficiently by concluding a contract. No matter to whom the entitlement is initially allocated, the allocation of the externality will ultimately reach the equilibrium when the producer is allocated the portion $w^*x^* + w^*p(x^*)D$ and the consumer is allocated the portion $z^*y^* + z^*p(y^*)D$.

An important conclusion of this section, therefore, is that given that the transaction cost is zero and information is perfect together with other important assumption such as fully competitive market and risk-neutrality, whatever the initial allocation, efficient allocation of the externality (in a bilateral accident where both parties' care level and activity level have an impact on accident cost) would be:

$$Producer: w^*x^* + w^*p(x^*)D$$

$$Consumer: z^*y^* + z^*p(y^*)D$$

Any further change from this condition would give rise to an increase in the full price and distort the optimal deterrence. Given zero transaction cost and perfect information, contractual parties will strive to coordinate with each other to minimise the full price of the product.[227] In this situation, without the application of liability rules, they can determine the allocation of externalities in a way that is consistent with the portions mentioned.[228] At this margin, the efficient outcome would be achieved, and relevant parties who have an impact on the cost of the accident will be incentivised to optimise their behaviour.

The analysis also touches on the fundamental controversy about the meaning of activity level and its distinction from care level. In general, what distinguishes activity level from care level is that people find that accident cost is not only correlated with efforts in terms of precaution but is also influenced by the amount and frequency of an activity. As analysed before, the way to achieve optimal care level is clear: if the cost of adopting a precautionary measure could reduce more expected harm than the case it is not adopted, relevant parties should be required to take it. Since the marginal cost of adopting a measure and the marginal expected harm it reduces are the criteria that can be assessed by everyone, the optimal care level in essence is a criterion that can be designed by contracts or legal instruments. In comparison, for a unit of activity, since its utility to different parties are different, parties may make different choices after comparing their own utility with the cost of such an activity. Therefore, as utility serves as a kind of information that can only be understood by the specific party, the optimal level of activity in theory is deemed as a criterion that cannot be found by outsiders or be designed by laws. The difference between care level and activity level, however, may not be a problem in the perfect world that is assumed in the beginning

[227] Hamada, Koichi. "Liability rules and income distribution in product liability." The American Economic Review 66, no. 1 (1976): 228-234; Epple, Dennis, and Artur Raviv. "Product safety: Liability rules, market structure, and imperfect information." The American economic review 68, no. 1 (1978): 80-95, at 83-87; Shavell (1980), supra note 217, at 14-16.

[228] See Hamada (1976), supra note 227.

of this chapter, because the involved parties are considered to hold perfect information meaning that they could even understand the others' utilities.

However, in recent years, some scholars have provided a different approach to distinguishing the activity level from the care level. Instead of interpreting the distinction from the perspective of quantity and intensity, the *observability* of an activity is chosen as the measure by these scholars.[229] Specifically, regardless of precaution or frequency/intensity, the activities that can be observed by regulators and courts fall into the category of care level, while those that cannot be observed are categorised as activity level. In this framework, some precaution-related behaviours that cannot easily be observed are no longer considered under the care level. The aforementioned blurriness between care level and activity level in essence is not a challenge to the distinction between care level and activity level, but it reflects the increasing difficulty of evaluating the optimal level of care as production becomes more complex than what we ever thought. As the knowledge in support of production turns to be more complicated than any period in history, the quest for optimal care level becomes difficult accordingly. As discussions in the following chapters implies, assessing the optimal care level is not a challenge for contractual parties, but it also results in a higher requirement for judges and regulators when they are deciding the liability or making regulations.

4.2. Contracting over product risk in an imperfect world

The discussion in the last section indicates that optimal deterrence can be achieved through bargaining. However, this conclusion is obviously limited by some essential assumptions. For example, it is assumed that the transaction cost is low when the producer and consumer attempt to reach an agreement and that each of the involved parties holds enough information. Put differently, the extent to which a consumer will punish the producer for unsafe products and reward it for safe products is significantly determined by whether or not a consumer can conclude a contract with

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[229] See Dari-Mattiacci, G. "On the Definitions of Care and Activity Level and the Choice of Liability Rules." (2003). Available at: https://dspace.library.uu.nl/bitstream/handle/1874/723/c3.pdf?sequence=24. See also, Garoupa, N., & Ulen, T. S. "The economics of activity levels in tort liability and regulation." In Thomas Miceli and Matthew Baker (ed). RESEARCH HANDBOOK ON ECONOMIC MODELS OF LAW, 33 (2013). Edward Elgar Publishing. Professor Parisi seems to adopt a compromise way to distinguish care level and activity level. He defined activity level as "the other factors that are not taken into account by courts to ascertain negligence the intensity and duration of the parties; activities." See Parisi, F. (2013), THE LANGUAGE OF LAW AND ECONOMICS: A DICTIONARY. Cambridge University Press.

the producer and whether or not a consumer has been well informed about product risk at the time.[230] In addition, it is assumed that all the involved parties are risk-neutral, so that allocating risk only depends on the deterrence effect.[231]

The assumptions abovementioned are reasonably observed at the early stage of production. Firstly, the producer took charge of every aspect of production, ranging from acquiring raw materials to manufacturing, distribution, and placing the final product in the market. As no new party engaged in the supply chain, it was relatively easy to allocate risk directly between the producer and consumer. Secondly, as the producer operated the business stably in a market, a consumer could easily go to the physical market to communicate with the producer and compare the product with the one from other sellers in the market before reaching an agreement.[232] From this perspective, consumers were expected to have sufficient information. At last, consumers showed little difference from producers in terms of their attitudes toward risk. Producers as individuals might not be less risk-averse than consumers.

Against the background aforementioned, this section explains that in reality parties can be frustrated at the time of concluding the contract.[233] Consider the fact that parties may not reach an agreement on risk allocation smoothly, that parties may not hold enough information in support of their bargaining and that parties could be different in light of their attitude toward risk, the efficiency of risk allocation will be distorted. In other words, the first-best solution, which is achieved by contractual relations, is not guaranteed in reality due to multiple barriers.

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[230] See Goldberg, Victor P. "Toward an expanded economic theory of contract." Journal of Economic Issues 10, no. 1 (1976): 45-61; Polinsky, A. Mitchell, and Steven Shavell. "The uneasy case for product liability." Harv. L. Rev. 123 (2009): 1437, at 1445.

[231] Other factors like market power can also tremendously distort the efficiency of bargaining over product risks. When consumers misperceive information, market power can play a crucial role in determining the effect of deterrence and in indicating the superiority of liability rules. See Polinsky, A. Mitchell, and William P. Rogerson. "Products Liability, Consumer Misperceptions, and Market Power." The Bell Journal of Economics 14, no. 2 (1983): 581-89; Spence, A. Michael. "Monopoly, Quality, and Regulation." The Bell Journal of Economics 6, no. 2 (1975): 417-29.

[232] Geistfeld, Mark A. PRINCIPLES OF PRODUCT LIABILITY, Foundation Press Thomson/West. 2011, at 11.

[233] As Viscusi identifies, "information and transaction costs make complete internalization of the costs of risk impossible. The resulting risk-reduction incentives exist at less than efficient levels, giving rise to a greater than optimal number of accidents." See Viscusi, W. Kip. "Toward a diminished role for tort liability: social insurance, government regulation, and contemporary risks to health and safety." Yale J. on Reg. 6 (1989): 65. See also, Mackaay, E. LAW AND ECONOMICS FOR CIVIL LAW SYSTEMS. Edward Elgar Publishing. 2013, at 416.

4.2.1. The limitation of contracting for product risk: where transaction cost is prohibitive

The first assumption for efficiently contracting over product risk is that all the relevant parties can bargain with each other freely and finally they can reach an agreement that satisfies all of them. This is also enshrined in the so-called "relativity of contract"[234] principle. In this regard, only contractual parties are bound by the contract concluded through bargaining, while any other third parties cannot claim a right or undertake an obligation based on the contract.[235]

The justification for the privity of contract can be explained by economic theory. On the one hand, a non-contractual party cannot claim a right based on the contract, because contractual parties have no anticipation of this third party at the moment of concluding the contract.[236] On the other hand, an obligation cannot be placed on a third party in the contract, since contracting on the loss of non-contractual parties can generate an externality to others.[237] Therefore, if contractual parties expect to include a third party into a contractual relationship or, conversely, if a third party expects to enter a contractual relationship with the current parties, an express consensus by all the parties is required. Only in this way can the extent to which a party is exposed to product risk or to which the behaviour of a party has an impact on accident cost be fully bargained and correctly evaluated within the contract.

In a scenario that the number of relevant parties is low or that numerous parties can find a way to conclude a contract together, risk can be allocated through one contract, to which all the parties

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[234] The wording of "relativity of contract" is commonly used in civil law countries. In a jurisdiction that is rooted in common law tradition, it is usually called the "privity of contract". See Ebers, M., Janssen, A., & Meyer, O. 2009. "Comparative report." In EUROPEAN PERSPECTIVES ON PRODUCERS' LIABILITY: DIRECT PRODUCERS' LIABILITY FOR NON-CONFORMITY AND THE SELLERS' RIGHT OF REDRESS, by André Janssen, Olaf Meyer Martin Ebers, 3-76. De Gruyter, at 4.

[235] In case law, the principle of the "relativity of contract" or the "privity of contract" was established in the Case *Winterbottom v. Wright* in 1842. In this case, Winterbottom was a contracted postman with the Postmaster, while Wright concluded a contract with the Postmaster to provide a mail coach. In a delivery, Winterbottom was injured due to the collapse of the coach. He filed a lawsuit to Wright claiming that his injury was caused by Wright's negligence. The court dismissed the action grounded that Wright was not privy to Winterbottom. See *Winterbottom v Wright* (1842) 10 M&W 109.

[236] As what has been cleared articulated in the verdict of the case Winterbottom v. Wright, "if the plaintiff can sue, every passenger, or even any person passing along the road, who was injured by the upsetting of the coach, might bring a similar action." See *Winterbottom v Wright* (1842) 10 M&W 109, at 114.

[237] Mackaay (2013), supra note 233, at 417.

are subject. However, sticking to the principle of privity of contract omits the situation where a single contract cannot include all relevant parties. This phenomenon is not uncommon in the aftermath of the Industrial Revolution.[238] In particular, the prohibitive transaction cost stems from two sources. Firstly, the increasing complexity of production determines that a single party cannot handle production in all aspects. The fact that a producer has to outsource some activities to other professionals for the purpose of lowering production cost determines that a chain of contracts is gradually formed along with the linear supply chain, which dilutes the privity between the producer and the consumer. Secondly, an increasing number of bystanders feel frustrated with the remedy based on the contractual relationship, since they face prohibitive cost in reaching an agreement with contractual parties at the time of concluding the contract.[239]

The emerging chain of contracts along the linear supply chain

The first scenario that increases the transaction cost of contracting for product risk is linked with the transformed chain of contracts.

As a result of the Industrial Revolution, two disruptions were obvious in the sector of production. Firstly, economies of scale dominated the pattern of production. Therefore, a producer had to invest heavily in advanced machines and any method that could help reduce the marginal price so as to gain a competitive position in the market. Secondly, the development of international transportation enabled producers to find suppliers with cheaper raw materials and to sell their products in foreign markets. This latter trend, while promising bright prospects for producers, generated costs in terms of operating transportation, building warehouses, and opening stores internationally. In order to focus on production activities, producers sought parties who could undertake relevant activities at a lower cost. As a result, a variety of intermediaries became involved in the supply chain.

[238] Katz, Avery. "The strategic structure of offer and acceptance: game theory and the law of contract formation." Mich. L. Rev. 89 (1990): 215.

[239] Landes, William M., and Richard A. Posner. "A positive economic analysis of products liability." The Journal of Legal Studies 14, no. 3 (1985): 535-567, at 543-544; Gilead, Israel. "Coase Theorem." Competitive Market and Products Liability Law." Israel Law Review 20, no. 1 (1985): 39-48.

As these intermediaries took on roles in transferring products from the producer to consumers, a contract could no longer be concluded directly between the producer and consumers. Figure 21 shows what the new supply chain looks like. In this context, the original direct contractual relationship between the producer and consumers is replaced by a linear chain of contracts. A manufacturer has an instant relationship with various suppliers, which then conclude contracts with various retailers in order to place products into different markets. Assuming that these intermediaries exchange every piece of information between the manufacturer and consumers and contribute to zero risk in the process of delivering products, replacing the single contract between manufacturer and consumer with a chain of contracts makes no difference in light of risk allocation. However, as we can see from Figure 18, the complex supply chain indicates that consumers cannot check up on the behaviours of manufacturers all the time and relevant information may be delivered to them only after they have purchased the product. What makes the situation more complicated is that the behaviours of intermediaries are by no means immune from risks, so that the causal inference between the activity taken by the producer and the damage caused to the consumer could be ambiguous.

To summarise, while the emergence of intermediaries lowers the transaction cost of delivering goods from producers to consumers, their existence dilutes the privity between the producer and the consumer by tremendously increasing the transaction cost between them in bargaining over producer risks. As a result, the increasing transaction cost involved in concluding a contract directly between the producer and consumer distorts the performance of the contract in allocating the product risk.

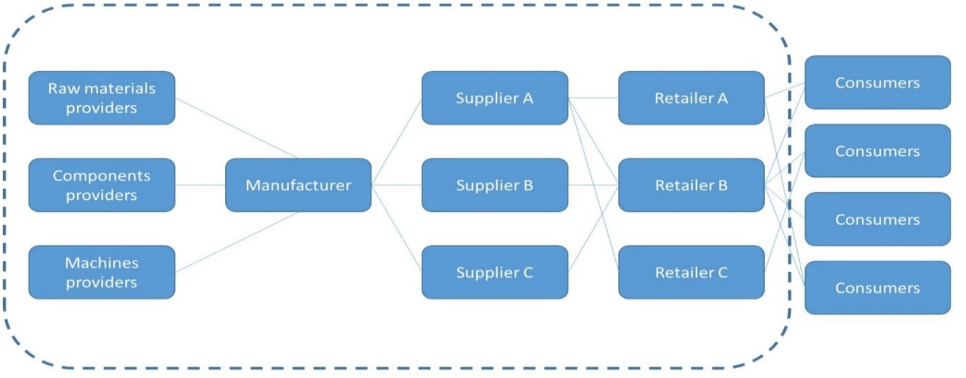

Figure 18: Supply chain in modern mass production

The increasing exposure to product risk for bystanders

Transaction cost also serves as an insurmountable obstacle for bystanders (i.e., the non-contractual parties who are damaged by using the product) to claim their losses.[240] The product risk caused to a non-contractual party was not widely witnessed in the early stage when a product was mostly used for personal consumption. In comparison, in the aftermath of the Industrial Revolution, as third parties could access a variety of products,, they were exposed to extensive product risk. For example, a product might be placed in a public area after it was purchased. In this case, since the bystander faced a prohibitive transaction cost to reach an agreement with the producer before the accident occurred, s/he could not claim for loss based on the terms of a contract.[241] Without an opportunity to bargain with the producer, the potential damage caused to a bystander could not be clearly understood by the contractual parties when they were concluding the contract. Contractual relationship, therefore, failed to play a role in allocating product risk in the case where third parties were as highly exposed to risk as consumers.

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[240] Faure, Michael. "Economic analysis of product liability." In Piotr Machnikowski. EUROPEAN PRODUCT LIABILITY: AN ANALYSIS OF THE STATE OF THE ART IN THE ERA OF NEW TECHNOLOGIES. Intersentia, 2017, 619-665, para 50.

[241] McKean (1970), supra note 233, at 620-621.

The discussion in this subsection explains that after the Industrial Revolution, the difficulty to reach an agreement of risk allocation among all stakeholders increases. In this regard, product risks may not be fully allocated at the time of concluding the contract, so that socially optimal deterrence cannot be achieved. The extent to which the factors increasing transaction cost will influence contracting over product risk in the context of 3D printing will be discussed in Chapter 5.

4.2.2. The limitation of contracting for product risk: where information asymmetry matters

Apart from the prohibitive transaction cost, the effect of contracting for product risk is also constrained by information problems.[242] The decision-making of a party is contingent on the information it holds. If the party has access to sufficient information, it can precisely compare the utility with the cost and further act in a socially optimal way.[243] The critical question to be answered here is whether sufficient information can be disclosed through private bargaining.

The sources of information asymmetry

According to the analysis above, no matter how the entitlement relating to product risk is initially allocated, given zero transaction cost and perfect information, in the case where both parties' care and activity levels influence the cost of an accident, optimal deterrence will result. The ultimate allocation of the accident cost would be:

$$\text{Producer: } w^*x^* + w^*p(x^*)D$$

$$\text{Consumer: } z^*y^* + z^*p(y^*)D$$

[242] Goldberg, Victor P. "The economics of product safety and imperfect information." The Bell Journal of Economics and Management Science (1974): 683-688; Spence, Michael. "Consumer misperceptions, product failure and producer liability." The Review of Economic Studies 44, no. 3 (1977): 561-572; Landes, W. M., and Richard A. Posner. THE ECONOMIC STRUCTURE OF TORT LAW. Harvard University Press. (1987), at 280-281; Geistfeld, Mark. "Manufacturer moral hazard and the Tort-contract issue in products liability." International Review of Law and Economics 15, no. 3 (1995): 241-257.

[243] Farrell, Joseph. "Information and the Coase theorem." Journal of Economic Perspectives 1, no. 2 (1987): 113-129, at 115-116.

Obviously, if this condition is correctly included in the provisions, the socially optimal incentive would be provided to contractual parties. This socially optimal outcome, however, should meet two conditions: information is not under-produced, and information is not asymmetrically distributed.

Firstly, every contractual party must be able to find the socially optimal outcome correctly; thus, they have to make every effort to acquire safety information and they must have the capacity to understand it.[244] This proposition, however, may not be fully observed in reality. The production of information is by no means costless. If the cost to produce information is very high, there will be less incentive for parties to acquire and understand such information. Therefore, rational parties will stop collecting information at the point where the marginal cost of producing information is higher than the marginal damage that is caused due to the lack of such information. As a result, in reality, the cost of information implies that contracting for product risk will always rest on incomplete information.[245]

Secondly, the information that is collected must be accessed and understood in the same way by the contractual parties. A producer has to evaluate precisely the decisive information from the side of the consumer.[246] Likewise, the consumer should also have the same capacity to understand the critical information relating to the producer.[247] Such information not only includes the optimal level of care that the opposite party should adopt, but also covers the optimal intensity and quantities of the activities from the other side. In practice, the level of difficulty of acquiring and understanding information is not the same between contractual parties. Often, one contractual party can obtain relevant information at less cost than the other.[248] Since the Industrial Revolution,

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[244] Stigler, George J. "The economics of information." Journal of political economy 69, no. 3 (1961): 213-225; see also Croley, Steven P., and Jon D. Hanson. "Rescuing the revolution: The revived case for enterprise liability." Michigan Law Review 91, no. 4 (1993): 683-797.

[245] See Epple and Raviv (1978), supra note 227; Polinsky and Rogerson (1983), supra note 231.

[246] Such decisive information includes the optimal care level of the consumer, the optimal activity level of the consumer as well as the probability of the accident given by the behaviours of the consumer.

[247] Such decisive information includes the optimal care level of the producer, the optimal activity level of the producer as well as the probability of the accident given by the behaviours of the producer.

[248] Kronman, Anthony T. "Mistake, disclosure, information, and the law of contracts." The Journal of Legal Studies 7, no. 1 (1978): 1-34, at 4; Mishra, Debi Prasad, Jan B. Heide, and Stanton G. Cort. "Information asymmetry and levels of agency relationships." Journal of Marketing Research 35, no. 3 (1998): 277-295.

production has increasingly become a professional activity. Producers invest a vast amount of money in employing advanced machines and techniques in support of their production. Also, by collecting and analysing a large volume of data, the ability of producers to acquire and to understand the behaviour of consumers has improved tremendously.[249] Therefore, it is reasonable to assume that, in the aftermath of the Industrial Revolution, producers hold more information than consumers.[250]

In reality, even if the producer holds the perfect information, it is highly likely that it will decide not to reveal it to others.[251] The reason is that the producer obviously knows that disclosing relevant information will have an impact on the decision-making of others, which will ultimately affect the producer significantly.[252] The literature implies that if the disclosure of information is costly to producers, they only have the motive to reveal the information up to the level at which the quality of their products exceeds a threshold.[253] Therefore, the producer may only choose to disclose favourable information voluntarily.[254]

Given the unequal ability to gain and understand information, consumer's decision-making is not, in reality, based on perfect information. In particular, two problems influence consumer decision-making.

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[249] Owen, David G. "Punitive damages in products liability litigation." Michigan Law Review 74, no. 7 (1976): 1257-1371.

[250] Daughety, Andrew F., and Jennifer F. Reinganum. "Economic analysis of products liability: theory." In Jennifer Arlen (ed.) RESEARCH HANDBOOK ON THE ECONOMICS OF TORTS. Edward Elgar Publishing 2013, at 69-96.

[251] Polinsky, A. Mitchell, and Steven Shavell. "Mandatory versus voluntary disclosure of product risks." The Journal of Law, Economics, & Organization 28, no. 2 (2010): 360-379. Information problem according to the diligence of producer can be generally divided into three types: (1) fraudulent misrepresentation, where a contractual party intentionally release fraud information; (2) negligent misrepresentation, where a contractual party fails to behave diligently in the disclosure of information; and (3) innocent representation, where contractual parties have behaved diligently, but the information disclosure is still insufficient. See Zhou, Qi. "Contractual mistake and misrepresentation." In Gerrit De Geest. ENCYCLOPEDIA OF LAW AND ECONOMICS. Volume 6. Edward Elgar Publishing Limited, 2009, at 31-56.

[252] See Farrell (1987), supra note 243, at 117.

[253] Viscusi, W. Kip. "A Note on" Lemons" Markets with Quality Certification." Bell J. Econ 9 (1978): 277-79; Jovanovic, Boyan. "Truthful disclosure of information." The Bell Journal of Economics 13 (1982): 36-44.

[254] Shavell, Steven. "Acquisition and disclosure of information prior to sale." The RAND Journal of Economics (1994): 20-36.

Firstly, the consumer may be *uncertain* about product safety given the information at hand and, as a result, may overestimate or underestimate the safety of a product.[255] In reality, with the complexity of the production process, contractual parties may be uncertain about the probability of a risk when they conclude the contract.[256] The literature on psychology shows that people rely on heuristics in the face of uncertainty. This means that factors such as experience over a long period, memory, and emotion, take on an important role.[257] A consumer tends to weigh what is perceived as negative information disproportionately.[258] For example, if consumers see news item mentioning that a person has been injured using a product, they are inclined to conclude that the product has a higher probability of causing damage. As a result, they tend to overestimate the risk.[259] In contrast, in *most* situations where consumers are imperfectly informed about product safety, the cognitive system based on heuristics may not be used in decision-making. Thus, as the literature implies, consumers tend to underestimate product risk in the situation when they have no idea about the probability of damage caused by a product.[260]

Secondly, apart from uncertainty, consumers may also systematically err in assessing the information and end up making the wrong decision.[261] A consumer may misperceive the optimal *care level* that should be taken by the producer. For example, in a particular case, five different kinds of safety device are required in order to reach the optimal care level for the production of a

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[255] Daughety, Andrew F., and Jennifer F. Reinganum. "Markets, torts, and social inefficiency." The RAND Journal of Economics 37, no. 2 (2006): 300-323; see also Daughety, Andrew F., and Jennifer F. Reinganum. "Communicating quality: a unified model of disclosure and signalling." The RAND Journal of Economics 39, no. 4 (2008): 973-989.

[256] Kaplow, Louis. "Optimal deterrence, uninformed individuals, and acquiring information about whether acts are subject to sanctions." JL Econ & Org. 6 (1990): 93.

[257] Tversky, Amos, and Daniel Kahneman. "Judgment under uncertainty: Heuristics and biases." science 185, no. 4157 (1974): 1124-1131.

[258] Weinberger, Marc G. "Products as targets of negative information: Some recent findings." European Journal of Marketing 20, no. 3/4 (1986): 110-128; Einhorn, Hillel J., and Robin M. Hogarth. "Decision making under ambiguity." Journal of Business (1986): 225-250.

[259] This phenomenon also explains why producers are reluctant to disclose safety information actively. See Schwartz, Alan. "Proposals for products liability reform: A theoretical synthesis." Yale LJ 97 (1987): 353.

[260] Latin, Howard. "Good warnings, bad products, and cognitive limitations." UCLA L. Rev. 41 (1993): 1193. Also, as what is articulated by Spence, "The mere fact that products may fail or cause accidents is not by itself an argument for intervention in the market. Nevertheless, because of the random character of the outcome, there is a suspicion that consumers are not accurately informed about the distribution of possible outcomes prior to purchase." See Spence (1977), supra note 242.

[261] Geistfeld, Mark A. "Imperfect Information, the Pricing Mechanism, and Products Liability." Columbia Law Review 88, no. 5 (1988): 1057-1072.

toaster. If consumers are fully aware of the requirements for these devices, they will check whether all five devices have been installed before purchasing the toaster. However, if consumers can only discern four of the five measures and fail to conclude all of the five measures into the contract, the producer will be induced to take a level of care up to installing the four devices. In this circumstance, without the intervention of other instruments to correct this insufficiency, the producer will not be induced to take a higher level of care, since any incremental precaution cannot be rewarded.[262] As a consequence, the optimal level of care is not fulfilled. Furthermore, a consumer cannot observe the optimal *activity level* that should be taken by the producer. In many cases, activity level refers to the element (e.g. the utility of a party) that is less observable than it would be if it was related to the level of care. In the production sector, a variety of activities from the producer's side, ranging from their utility to their frequency of activities, may be hard for consumers to observe. Suppose that a producer has two plans for a product: Design A could increase the utility for consumers by 10 units, but it increases product risk by 20 units, while Design B increases consumers' utility by 5 units at the expense of 5 additional units of risk. If consumers hold complete information, they will choose Design B instead of Design A. However, if consumers can perceive the incremental utility obtained from a product but cannot distinguish the expected harm for a given activity level (i.e., different designs), they will make the wrong decision. As a result, since an increase in activity level is not observed by consumers, the producer would be induced to opt for excessive activities and tend to adopt risky plans.[263]

To summarise, the discussion above explains how information could be asymmetrically possessed by contractual parties. In practice, due to the existence of information asymmetry, one contractual party could hardly understand the optimal level of activity of the opposite party, or s/he might misperceive the optimal level of precaution that the other party should adopt. As a result, contractual parties may not be incentivised to behave appropriately. Having said that, people may wonder whether other signals are available in the course of bargaining, which may reduce the information asymmetry between contractual parties. The following discussion in this subsection will analyse how warranties are perceived as a promising signal of product safety and what further problems arise there.

[262] See Shavell (2009), supra note 212, at 53.

[263] See Spence (1977), supra note 242.

The function of warranties and its implications for information problems

Warranties refer to "a promise of the seller to take contractually specified measures in case the performance of the purchased item is bad".[264] If the product fails to perform in the way promised by the producer, the consumer can claim in the warranty what has already been promised by the producer. Typically, warranties not only include the replacement or repair of defective goods and price refunds but, in some cases, they also contain reimbursement for damages.[265]

As consumers cannot precisely distinguish the products of good quality from those of bad quality, they will make decisions at the average market price. Since producers are not rewarded by a competitive advantage in the market through investing extra effort on precaution, they will not be induced to produce products of higher quality. In these circumstances, the problem of adverse selection is severe and a "market for lemons" is formed.[266] The existence of the "market for lemons" also harms a producer with high-quality products, because its good products cannot be differentiated from the bad ones. One solution for overcoming this adverse selection problem is to provide consumers with credible information.[267] If consumers can correctly link credible information with product safety, their decision-making might be improved. In order to sell the

[264] Wehrt, Klaus. "Warranties." In Bouckaert, Boudewijn and De Geest, Gerrit (eds.), ENCYCLOPEDIA OF LAW AND ECONOMICS. Volume 3, Edward Elgar Publishing. 2000, at 179. In turn, as Emons defined, warranties also "constitute a claim for the buyer on what a seller will do in the event of product failure". See Emons, Winand. "The theory of warranty contracts." Journal of Economic Surveys 3, no. 1 (1989a): 43-57.

[265] See Emons (1989a), supra note 264, at 43; Gal-Or, Esther. "Warranties as a Signal of Quality." Canadian Journal of Economics (1989): 50-61; Mann, Duncan P., and Jennifer P. Wissink. "Money-Back Warranties Vs. Replacement Warranties: A Simple." The American Economic Review 80, no. 2 (1990): 432.

[266] The phenomenon of "lemon" markets was firstly discussed by Akerlof. This phenomenon refers to the problem, which is also called "adverse selection", where price mechanism fails to differentiate the product with lower risk from the one with a higher risk in the case where consumers are imperfectly informed. The detriment of adverse selection is that as the products with better qualities cannot be precisely identified by the consumer via the price mechanism, so that they may not be chosen by consumers in the end. At last, the products with good qualities are gradually excluded from the market, which ultimately only accommodates for the products with bad qualities. See Akerlof, G.A. "The Market for "Lemons": Quality Uncertainty and the Market Mechanism." The Quarterly Journal of Economics, 84:3 (1970): 488–500.

[267] Spence, Michael. "Informational aspects of market structure: An introduction." The Quarterly Journal of Economics (1976): 591-597, at 592.

goods to consumers, producers of high-quality goods have an incentive to disclose information voluntarily to provide evidence that their products are of high quality.[268]

In theory, a product warranty is an appropriate signal of product safety.[269] By voluntarily promising coverage to consumers, the producers are de facto sending consumers the information about the effort made to invest in improving product safety and highlighting the superior quality of the product.[270] Because the coverage promised by the producer has to be guaranteed at the time when damage is caused to the consumer, warranties are linked to the price mechanism by their nature.[271] Therefore, product warranties serve as a credible signal to consumers in theory, even though consumers have no experience of the product.[272]

For the same type of product, consumers can differentiate between good and bad quality in two ways. Firstly, if consumers find that a product is offered at the same price as others but with a broader scope of product warranties, they can reason that a higher level of quality is implied.[273] Secondly, if consumers find that a product is offered with the same product warranties but at a lower price, they can also reasonably expect that this product is superior to others in terms of product safety.[274]

The signalling function of product warranties has a massive impact on deterrence. In order to distinguish their high-quality products from others, producers have the incentive to optimise their

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[268] See Viscusi (1978), supra note 253; see also Jovanovic (1982), supra note 253.

[269] The signalling function of the warranty was firstly found by Spence. See Spence, Michael. MARKET SIGNALING: INFORMATIONAL TRANSFER IN HIRING AND RELATED SCREENING PROCESSES. Vol. 143. Harvard University Press, 1974. See also Grossman, Sanford J. “The informational role of warranties and private disclosure about product quality.” The Journal of Law and Economics 24, no. 3 (1981): 461-483; Priest, George L. “A theory of the consumer product warranty.” The Yale Law Journal 90, no. 6 (1981): 1297- 1352, at 1303-1307; Wiener, Joshua Lyle. “Are warranties accurate signals of product reliability?” Journal of Consumer Research 12, no. 2 (1985): 245-250; Lutz, Nancy A. "Warranties as signals under consumer moral hazard." The Rand journal of economics (1989): 239-255; Kirmani, Amna, and Akshay R. Rao. “No pain, no gain: A critical review of the literature on signaling unobservable product quality.” Journal of marketing 64, no. 2 (2000): 66-79.

[270] See Grossman (1981), supra note 269; see also Cooper, R., & Ross, T. W. (1985). Product warranties and double moral hazard. The RAND Journal of Economics, 103-113.

[271] See Geistfeld (1988), supra note 261, at 1061-1062.

[272] See Priest (1981), supra note 269, at 1303.

[273] See Geistfeld (2009), supra note 239, at 296.

[274] See Spence (1974), supra note 269, at 88-90; Emons (1989a), supra note 264, at 44 and 47; Wehrt (2000), supra note 264, at 183.

behaviours. In particular, producers are induced to invest in product safety up to the point where the marginal cost equals the marginal benefit. At this point, since any deviation would result in a higher cost, the accident cost would be minimised. Accordingly, the price of the warranties that are offered to consumers will also be minimised.

When we are talking about the signalling function of warranties, we are actually assuming that consumers have access to the terms and prices of the warranties offered by every seller in the relevant market. However, this assumption may not necessarily hold in reality.[275] As the warranties that confront the consumer are made for different time periods and supported by inconsistent data, the consumer cannot readily make an efficient decision. The complexities, in reality, imply that consumers may not easily determine the expected cost (i.e., the value of warranties) so they cannot decide whether it is themselves or the producer that can avoid specific risks at the least cost.[276] In addition, product warranties as a way of signalling product risk can also be distorted when there is a low level of competition in the market; if there are few alternatives to a product and a producer has monopolistic power in the market, the coverage of warranties will be greater than consumers require.[277]

Also, even though we assume that the market is competitive and that the cost of accessing information is negligible, consumer misperception is inevitable. As Priest articulates, "signals [of product warranties], however, only reduce information costs to consumers". [278] In reality, consumers often systematically err in evaluating the optimal scope of warranties that they should purchase. Thus, even if products of different quality are correctly differentiated through product warranties, the consumer may make wrong decisions by systematically underestimating or overestimating product risk. Firstly, if consumers incorrectly believe that a warranty offered by a producer has no impact on product risk or that they can self-insure a risk at a lower price than the

[275] Schwartz, Alan, and Louis L. Wilde. "Imperfect information in markets for contract terms: The examples of warranties and security interests." Virginia Law Review (1983): 1387-1485.

[276] In essence, under warranties, while the producer is incentivized to provide more information to differentiate his/her product with high-quality from other bad ones, at the end of the day it is the consumer that has to evaluate whether it is the producer or s/he that turns to be the party that can avoid particular risk at the cheapest cost. See Geistfeld (1988), supra note 261, at 1063.

[277] See Grossman (1981), supra note 269, at 465.

[278] See Priest (1981), supra note 269, at 1303. See also Spence (1977), supra note 242.

producers, they would place no value on this risk at the time when they purchase a particular warranty. As a consequence, instead of purchasing the product with the optimal scope of warranties as implied by signal theory, they may purchase the one with a limited scope of the warranty.[279] Secondly, consumers may also overestimate the optimal scope of warranties.[280] In this case, they mistakenly place a value on a guarantee that has no probabilistic influence on the accident or they mistakenly think that the producer, rather than themselves, can avoid risk at the lowest cost. As a consequence, consumers would be incentivised to purchase more warranties than they need. This misperception gives producers the incorrect signal that they have to offer more warranties. Otherwise, even though they offer the optimal scope of warranties, they will be regarded as selling products that are less safe. The economic implication of overestimating the optimal scope of warranties leads producers to expend excessive effort on precaution and impede new products from entering the market.

In reality, the occurrence of an accident usually not only rests on the behaviour of the producer but also on the behaviour of the consumer.[281] In this sense, once the product is transferred from the producer to the consumer, the performance and lifespan of the product can show significant variances under the control of different consumers since different consumers use the product at different frequencies and with different levels of caution.[282]

If producers can accurately differentiate the risk of various consumers and monitor their behaviours in every possible situation, they can correctly place a value on the costs generated by consumers. In this sense, as the cost generated by consumers will ultimately be internalised by them, they will be incentivised to behave appropriately. Provided that the consumer can also perfectly observe the costs generated by the producer, optimal deterrence will be accomplished. However, if the producer cannot correctly distinguish the risk posed by consumers, which is also the case probably observed in reality, it is de facto providing some warranties to risks that are correlated with the consumer. As analysed, in bilateral accidents, the behaviour of the victim also

[279] See Shavell (2009), supra note 212, at 61-62.

[280] See Shavell (2009), supra note 212, at 61.

[281] See Priest (1981), supra note 269, at 1311-1314.

[282] See Kambhu, John. "Optimal product quality under asymmetric information and moral hazard." The Bell Journal of Economics (1982): 483-492; Emons, Winand. "On the limitation of warranty duration." The Journal of Industrial Economics (1989b): 287-301

has a significant impact on the achievement of the socially optimal outcome. In the production sector, if consumers are not provided with an incentive to behave appropriately, since part of the costs are not internalised by them, they will be induced to take a lower level of precaution and to take on excessive activities. As a result, the socially optimal outcome might never be achieved.

4.2.3. Taking the issue of risk-spreading into consideration

The analysis above explains that, given low transaction cost and no information asymmetry, parties are expected to be incentivised to behave appropriately by contracting over product risk. According to law and economics theory, social welfare not only depends on deterrence but also on whether risk-averse parties bear risks.[283] Social welfare will be diminished if risk-averse parties have to bear risks. In fact, apart from providing the incentive to behave appropriately, parties may also shift the risk through bargaining. This subsection will discuss the extent to which parties are able to use risk-shifting clauses or warranties to shift risk, which could increase social welfare.

Four scenarios can be distinguished according to the risk preference of sellers and consumers.

The first is where both the seller and the consumer are risk-neutral. This circumstance is also consistent with the primary assumption made in Section 4.1. Since parties are indifferent to bearing risk either ex-ante or ex-post, adding a risk-shifting clause will simply increase the instrumental cost without increasing social welfare.[284]

Things change in the situation when one contractual party is risk-neutral while the other is risk-averse. Suppose that the consumer is risk-averse but the producer is risk-neutral. In this situation, deterrence efficiency will lead each party to bear the risk that is correlated with its behaviour. As the producer is risk-neutral in this case, either shifting the risk in advance or paying the loss afterwards makes no difference. However, the risk neutrality of the producer is of great importance to the consumer in this scenario, since the expected utility will increase if the consumer can shift the risk to the producer by paying some money in advance. In this case, the risk-neutral producer will include the relevant expected harm into the market price of the product. By doing so, an

[283] See Shavell (2004), supra note 2, at 257.

[284] Parisi, Francesco. "The harmonization of legal warranties in european sales law: An economic analysis." Am. J. Comp. L. 52 (2004): 403, at 409.

increase of social welfare is expected, since the risk-averse consumer is guaranteed to get rid of huge loss by paying a certain amount of money ex ante. In other words, given no adverse selection or moral hazard problems, providing warranties or setting up a clause to shift risk from consumers to producers is desirable when consumers are more risk-averse than producers.

Thirdly, suppose that the producer is risk-averse, but the consumer is risk-neutral. In this case, the consumer is indifferent to shifting the risk in advance or bearing it alone, because it has no impact on the expected utility. As a result, the producer will not be incentivised to provide any warranties in the contract to the consumer.[285]

Lastly, when the producer and consumer are both risk-averse, they both have an incentive to shift risk in advance. In this situation, without other instruments, none of the contractual parties is in the best position to bear the risk. Parties are thus inclined to bargain with each other, and they are induced to share the risk in a way to which they agree.

Having distinguished the four possibilities in light of the attitude of risk of the producer and consumer, it can be concluded that the function of contract regarding risk-shifting depends on the real situation. Contracting over product risk does not pose a big problem for risk-shifting when contractual parties are risk-neutral. In contrast, in the case that both parties are risk-averse, which means that both parties desire to shift risk to others, they may not achieve the goal simply through a contractual relationship. Having summarised that, the extent to which risk-shifting is needed ultimately depends on the real context.

Under mass production, it is reasonable to generalise that producers are less risk-averse than consumers, so that the second circumstance aforementioned might be the case. If the producer can include the expected harm into the term of the contract or offer warranties for that coverage, social welfare may not be greatly distorted from the perspective risk-shifting. However, it must be noted that not every producer has the capacity to self-insure. As production becomes more complicated, even mass producers have the motivation to shift risk. This fact indicates that producers are relatively less risk-averse than consumers in reality. Therefore, even in the era of mass production, it seems that the last scenario where both the producer and consumer are risk-averse is deemed as a reasonable case observed in reality.

[285] See Parisi (2004), ibid.

The fact that producers become risk-averse to some extent indicates that they may be reluctant to place risk-shifting terms into the contract or offer warranties separately. In this case, assuming no presence of other instruments, consumers who are also risk-averse cannot expect to shift risk by concluding contracts with sellers. Therefore, risk-averse consumers have to rest on other instruments to shift risk. In other words, contractual relationship may fail to maximise social welfare by optimising the behaviour of contractual parties and shifting risk at the same time. Other instruments are necessary for consumers

4.2.4. Summary

This section revealed how the effect of deterrence and risk-shifting could be distorted by contracting over product risk. Due to the prohibitive transaction cost and imperfect information in the course of concluding a contract, relevant parties may not be incentivised to optimise their behaviours. What is worse, whenever both contractual parties are risk-averse, the goal of risk-shifting may not be achieved by simply concluding a contract.

It is noted that despite the distortions caused by transaction cost and information problems, a group of scholars still have a strong belief in the role of market forces and contend that allocating product risk through contractual relationships is still preferable; interventions cannot do better than the market itself.[286]

4.3. Chapter conclusion

The main interest of this chapter is to analyse how product risk can be allocated between producers and consumers through bargaining and how an efficient outcome might be distorted in reality.

[286] For example, Peter Huber contends that producers should be imposed on the duty to fully disclose the information relating to product safety by proposing a "law of warning." See Huber, Peter W. LIABILITY: THE LEGAL REVOLUTION AND ITS CONSEQUENCES. Basic Books, (1988), at 213. Richard Epstein also expresses deep faith in contracting for product risk. According to the proposal of Epstein, warranties are produced in the market of products, and their performance would be efficient. See Epstein, Richard A. "The unintended revolution in product liability law." Cardozo L. Rev. 10 (1988): 2193.

The first section of this chapter concludes that the socially optimal outcome can be achieved through bargaining given specific conditions being met.[287] However, as is shown in Section 4.2, the assumptions are not easily satisfied in reality. In particular, it explains how transaction cost and information asymmetry can lead consumers to behave inappropriately in reality. In addition, it is also analysed in the same section how social welfare might decrease due to the need of risk-shifting cannot be satisfied by contractual relationship in reality.

Having analysed in Chapter 4 the issue of how deterrence and risk-shifting can be distorted given multiple factors being considered, Chapter 5 aims to pay close attention to the context of 3D printing. The goal of the next the chapter is to explore the extent to which the impact factors exist in different business models of 3D printing and more importantly, how these factors will influence the desirability of contractual relationship in light of deterrence and risk-shifting.

[287] See the discussion under Section 4.1.

Chapter 5. Contracting over the Product Risk in the Context of 3D Printing

The discussion in Chapter 1 showed that the value generated by the activities of 3D printing is mainly captured in two kinds of activities: the digital modelling and the physical manufacturing. As 3D printing applies to the production sector, production is transformed in a way that the consumer has to firstly acquire a CAD file from a digital designer and then s/he has to have it printed out by a separate fabricator that is a stranger to the designer. This new and fast-developing business model is called the "separation" model in this thesis. As Chapter 3 introduced, this "separation" model has been widely adopted in practice. The operation of the business focusing on digital modelling (Model A) or physical fabrication (Model B) could also be largely different.

Under the so-called "separation models", consumers play a dominant role in the choice of the digital designers and fabricators. They may also take on a role of coordinating the involved parties that come from different modules. Since the designer of the CAD file and the fabricator of the final product are strangers to each other, to complete a final product under "separation models", at least two times of bargaining are necessary. The first bargaining is between the consumer and the CAD file designer based in Model A, and the second one is between the consumer and the fabricator based in Model B. Supposing that bargaining within "separation models" is smooth, meaning that relevant parties could contact with each other in a costless way, that they do not suffer information asymmetry and that they are risk-neutral, the two agreements would provide contractual parties with the optimal incentive to behave appropriately and there would be no need to shift risk through contracts. In this situation, despite the existence of two times of bargaining, the efficient outcome can be achieved. However, Chapter 4 has further explained how socially optimal outcome can be diminished given the existence of prohibitive transaction cost, information asymmetry and risk-aversion in reality. This chapter explores what these implications mean for the product risk in the context of 3D printing. Specifically, the main interest of this chapter is to examine the extent to which the aforementioned barriers can prevent consumers from efficiently concluding contracts with the involved parties (i.e. digital designers and fabricators) either in Model A or in Model B. In addition, this chapter also discusses whether the issue of risk-shifting presents to diminish social welfare in the course of concluding the contract.

5.1. Contracting over the risk associated with CAD files

Under the "separation model", a consumer firstly has to obtain a CAD file before s/he finds another party to print it out. As analysed in Chapter 3, Models A covers all of the business models that provide consumers with CAD files. In practice, a consumer can get the CAD file through one of the three approaches. Firstly, a person can download a CAD file from an open-source platform (Model A.1). Secondly, a person can go to an online marketplace to purchase a CAD file from a seller who operates its business on the platform (Model A.2). Thirdly, a person can also get in touch with a digital designer directly without the assistance of an online platform (Model A.3). Under Model A, while in some cases (especially under Model A.3) the input by consumers may influence the behaviour of the CAD file maker, in most cases the behaviour of the consumer has little impact on the performance of the CAD file.[288] In other words, the deterrence effect is primarily constrained by the activities taken by the CAD file maker.

In an ideal setting, as analysed in Chapter 4, optimal deterrence is achieved provided that the victim and the CAD file maker are able to bargain with each other and they have no opportunity to hide information.[289] However, this assumption is rarely observed in reality. What is more, the risk-neutral assumption may not be met under Model A, indicating that additional risk-shifting tools other than contractual relationship are necessary.

5.1.1. Contracting over the risk associated with the CAD file under Model A.1

The emergence of Model A.1 is a spontaneous process.[290] On the one hand, Model A offers a way through which non-professional CAD file designers can share their creative ideas irrespective of

[288] See the interpretation in Section 3.3.1.

[289] See the interpretation in Section 4.1.

[290] See the interpretation in Section 3.3.1.

their capacity in digital design. On the other hand, people who need CAD files can free-ride others' innovation. Despite the potential of this business model, bargaining over product risk under Model A.1 may diminish the social welfare.

The prohibitive transaction cost

The transaction cost of bargaining over product risk could be insurmountable in Model A.1. One reason is that a digital design may have already been remixed tens of thousands of times before it reaches the final remixer and the downloader. As each CAD file maker may pose a risk as they contribute to the CAD file, an agreement should be reached among all of the involved designers in order to achieve the optimal outcome. However, reaching such an agreement is almost impossible, not only because the designers are strangers to each other, but also because the pool of engaging parties continues to be larger as new CAD file designers engage in remixing the CAD file. As a result, whenever a consumer downloads a CAD file from an open-source online platform, s/he automatically reaches an agreement with the final trader. Even if the defect that caused the damage is ultimately found to be linked with an individual further up the chain of remixing activities there is little chance for the victim to conclude a contract with the culprit in advance to allocate the risk generated by the CAD file.[291] In an open-source community, the CAD file designers may come from different areas, so it could be costly to form a chain of contracts to trace every digital designer. As many CAD file designers cannot be included into the contract, they may not be provided with the optimal incentive.

The inevitable information problem

What is worse, even if the downloader is able to reach an agreement with any party further up the supply chain, the contract concluded by them will frustrate the consumer due to the lack of information in support of bargaining.[292]

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[291] As professor Twigg-Flesner articulates, "if a CAD file is downloaded for free from an open-source site, the position might be less clear, and it is possible that there is no contract at all." See Twigg-Flesner, Christian. "Conformity of 3D prints–Can current Sales Law cope?" In R. Schulze and D. Staudenmeyer, DIGITAL REVOLUTION–CHALLENGES FOR CONTRACT LAW, Nomos/Hart, 2015, 35-65, at 47-48.

[292] Twigg-Flesner (2015), supra note 291, at 61.

In reality, consumers may have no idea of the real scale of the risk in a CAD file, so s/he has to rely on particular signals to evaluate the full price. Under this background, we wonder enough information can be produced and offered to consumers by concluding a contract. Under Model A.1, two factors explain why consumers may fail to understand the full price of the CAD file accurately.

On the one hand, in an open-source context, while the market price of a CAD file is *zero*, its full cost is not. Therefore, there is a chance that a consumer cannot accurately assess the risk with a CAD file through the signal of price. On the other hand, CAD file makers may not have the incentive and the capacity to disclose enough information to consumers under Model A.1. The previous discussion on warranties indicates that producers are indeed incentivised to provide consumers with warranties in a market setting since a lack of warranties implies a higher level of risk. However, in reality, warranties are rarely provided by sellers under Model A.1. Constrained by its capacity, the CAD file maker may be uncertain about specific technical specifications and their correlation with potential risks. In this regard, as an ordinary individual with (limited) digital design expertise, the CAD file maker is unable to know every potential risk associated with the CAD file. Taking this situation into consideration, the CAD file maker is inclined to opt not to offer warranties voluntarily.

The risk-shifting problem under Model A.1

To efficiently deal with the product risk, not only the relevant parties should be provided with optimal incentives, but the risk-averse parties should also not bear risk in the end.[293] In a scenario where producers are more risk-neutral while consumers are more risk-averse, risk-shifting turns not to be a big problem under the contractual relationship, because contractual parties may agree to place a coverage into the price of the product. By doing so, the risk-averse consumers will not bear risk in the end. This situation, however, is not the case under Model A.1. Unlike traditional manufacturing, under Model A.1 digital designers who pose risks to the CAD are mostly ordinary non-professionals. This transformation implies that few differences in terms of the risk attitude are identified between digital designers and consumers. As a result, the designer of the CAD file has

[293] See Shavell (2004), supra note 2, at 257.

no motive to provide warranties voluntarily. In this sense, while both parties need to shift risk, they may not shift risk to the other party by simply resting on concluding contracts. Therefore, additional instruments are demanded beyond the contract to shift risk.

5.1.2. Contracting over the risk associated with the CAD file under Model A.2

Model A.2 shares some similarities with Model A.1 concerning the source of CAD files. In this regard, non-professional digital designers also account for the majority of CAD files that are uploaded on the intermediary platforms. However, according to the analysis in Section 3.3.1, there are two critical differences between Model A.1 and Model A.2.[294] Firstly, unlike Model A.1 where a CAD file might be remixed by a number of parties, under Model A.2 one CAD file is normally accomplished by a single digital designer. Secondly, the price mechanism works in Model A.2, meaning that a consumer has to pay a price for the CAD file.

The open-source attribute of Model A.1 means that a chain of digital designers is involved in the remixing activities. Therefore, it will be incredibly costly for a consumer to identify the culprit and to bargain over the potential risk with this person. In comparison, Model A.2 operates as an online marketplace where the CAD file is completed by a single digital designer, so that the consumer is able to be associated directly with the digital designer. In this regard, compared with Model A.1, substantial costs of concluding a contract are saved under Model A.2.

However, reaching an agreement in a less costly way does not ensure that contracting over risk could lead to the optimal deterrence. Under Model A.2, the key to providing contractual parties with optimal deterrence is making sure that parties are aware of the full price of the CAD file. Admittedly, compared with Model A.1, information asymmetry might be less severe than that under Model A.2. Instead of reviewing the information of multiple people who are engaged in remixing activities, a buyer only needs to evaluate the information of a single trader to whom s/he is tightly linked in Model A.2. In addition, multiple additional signals (e.g. price and product description) can be perceived by a buyer in Model A.2. Problems arise, however, when it comes to the issue of whether consumers have access to sufficient information and whether they can precisely evaluate it. In this regard, in order to assess the full price of a CAD file accurately, a

[294] See the analysis under Section 3.3.1 in Chapter 3.

consumer has to understand several variables, ranging from the optimal level of precaution to the optimal level of activity and probability of damage. If the consumer underestimates the risk with a CAD file, s/he may wrongly choose the CAD file with a risky design, and the CAD file maker thereby will be incentivised to reduce the investment made in CAD safety.

To summarise, compared with Model A.1, the transaction cost and information asymmetry that confront the consumer seem to be lower. However, the fact that consumers may be not aware of the optimal precautions and activities that should be taken by the digital designer determines that some of the cost that should have been internalised by the digital designer is ultimately borne by the consumer.

Apart from the deterrence problem, similar to the observation under Model A.1, risk-shifting could be another issue that diminishes social welfare under Model A.2. As CAD file designers are not significantly risk-neutral compared with consumers, they are not motivated to offer coverage via contracts. As a result, both parties have to bear a portion of risk by themselves.

5.1.3. Contracting over the risk associated with the CAD file under Model A.3

Compared to Model A.1 and Model A.2, in which consumers have limited opportunities to explain their expectation to digital designers, a digital design under Model A.3 is accomplished through the close cooperation between designers and consumers. Take *Voodoo* as an example. A consumer can start a customised digital design project by merely sketching out a rough concept. Once the designer understands the specific demand of the consumer, the designer will start the digital modelling process. The original idea can be developed into a more concrete and viable one after a few rounds of discussions between the designer of *Voodoo* and the consumer.

Model A.3 ensures that consumers can sufficiently explain their ideas and demands to a professional digital designer. During the digital modelling process, the consumer can also maintain regular communication with the designer. Therefore, the contract concluded in Model A.3 is based on adequate bargaining. Through constant meetings with the digital designer, the consumer will be informed of the potential risk by the digital designer. In this respect, the digital modelling process under Model A.3 is also a process of reducing information asymmetry. Therefore, compared to the previous two business models for acquiring a CAD file, by removing the obstacles of concluding a contract and by disclosing more information to the consumer, bargaining over the CAD file risk under Model A.3 seems to promise a better deterrence effect. The CAD file maker, which runs a business within Model A.3, is thus expected to behave more cautiously.

However, information problems cannot be completely eliminated within this business model. As explained, in the case where private parties cannot produce information in a costless way, the optimal level of precaution cannot be precisely found through bargaining. Also, as the literature shows, even if the CAD file maker serves as the party that holds the most information, it may not be incentivised to inform the consumer fully.[295] Taking these points into account, while bargaining over risk under Model A.3 indicates that the producer would be incentivised to take necessary precautions, its investment in the safety of the CAD file would be limited to the extent that is observable to consumers. In other words, a digital designer would not be incentivised to take precautions to the extent that cannot be factored in by consumers**,** since these additional investments will not be rewarded by way of a higher market price.

From the perspective of risk-shifting, while CAD file providers seem to hold more capacities than the ones under Model A.1 and A.2, they are not as risk-neutral as people expect. In reality, warranties on the performance of the CAD file are rarely provided voluntarily by the producers that operate under Model A.3.[296] Three reasons account for it. Firstly, just as observed under Model A.1 and Model A.2, technical uncertainties prevent CAD file makers from offering warranties voluntarily. Secondly, as the behaviour of consumers is becoming more crucial in obtaining CAD files, CAD file makers cannot easily split the risks generated by the guidance of the consumer from the risks generated by their own modelling. At last, as digital designing under Model A.3 is a way featured by customisation, the CAD file designer could hardly spread risk through price among a huge group of consumers.

To summarise, compared with Model A.1 and Model A.2, Model A.3 seems to promise a better effect on deterrence. However, contractual parties are only provided with the incentive to behave appropriately to the extent that the opposite party can observe. In other words, the level of activity might not be optimised under Model A.3. Also, risk-shifting may still be problematic within

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[295] See the discussion in Section 4.2.2.

[296] It is investigated that no warranties are voluntarily provided by the websites (e.g. *Voodoo, Shapeways, i.materialise*) who offer the CAD file modelling service at the current stage.

contractual relations as CAD file designers as SMEs are not motivated to provide enough coverage to consumers via contractual terms or warranties.

5.1.4. Summary

The analysis above explained that the deterrence effect shows a substantial divergence under different business models. It is concluded that CAD file makers are least motivated to optimise their behaviours under Model A.1, where CAD files are transacted for free in an open-source environment. The deterrence effect is expected to be improved to some extent under Model A.2, due to the decrease in the cost of reaching an agreement and the variety of signals perceived by consumers. The contractual relationship shows a greater potential in terms of optimising deterrence under Model A.3, where close collaboration between CAD file makers and consumers ensures that the former ones optimise their behaviour to the extent that can be *observed* by the consumer. Therefore, consumers have to take extra efforts to inspect the safety of the CAD file, if they decide to acquire a CAD file under Model A.1 and Model A.2. Consumers may have to bear more cost than expected under these two models. Without the intervention of other instruments, consumers' confidence in the reliability of the design might be ruined in the long run.[297] In addition, given no other risk-shifting instruments, risk-shifting could be a problem under all kinds of business models, because the designers who offer CAD files under Model A turn out to be reluctant to provide a way of shifting and spreading the risk.

5.2. Contracting over the risk associated with the physical fabrication

In the context of 3D printing, the function and quality of a final product are substantially determined by the process of digital modelling, while the printing activity is generally regarded as a process that follows the instructions in the codes embedded in the CAD file.[298] However, it does not mean that the process of fabrication does not creates no risk to the final product.[299] The printer

[297] See Harris (2015), supra note 1.

[298] See the discussion under Section 1.3.2 in Chapter 1.

[299] For the risks posed by fabricators, see the analysis in Section 1.3 and Section 3.3.2.

that is used by the fabricator and the diligence of the fabricators can also affect the performance of the physical product.

After contracting with the CAD file designer and getting the CAD file thereafter, the consumer has to reach another agreement with the fabricator. Fabricators must be provided with the optimal incentive in proportionate to the risk generated by them. The extent to which the consumer can reach such an agreement efficiently with the fabricator depends on the concrete context that the final product is printed. Under different contexts, since the difficulties of contracting over product risk are quite different, the incentive that is offered to the fabricator to behave appropriately is also not the same.

As introduced in Chapter 3, a consumer has three options to print out the CAD file. Firstly, CAD file holders can have the product fabricated by uploading the CAD file onto a professional platform (Model B.1). Secondly, the file holder can seek a nearby printing hub on an online marketplace (Model B.2). Thirdly, the file holder can go to an intermediary platform, which offers no fabrication service but has extensive relations with professional fabricators (Model B.3). The main interest of this section is to explore the effect of deterrence and risk-shifting in different business models.

5.2.1. Contracting over the risk associated with physical fabrication under Model B.1

At present, the most common approach for a CAD file holder to have a CAD file printed is to seek the help of a professional platform, which owns different types of 3D printers and offers a wide range of solutions. Under this business model (i.e., Model B.1), consumers start the process by uploading CAD files. Further, consumers can choose their preferred materials, size, and colour in turn, and the final price will be shown for the customised demand. Once a fabricator receives an order, it will start the fabrication process according to the consumer's detailed requirements. Lastly, the fabricator will deliver the final product to the customer.

Model B.1 is already a mature business model, and an increasing number of professional fabricators are running their businesses by setting up their own online platforms. In order to compete for an advantageous place in the market, they make considerable investments to buy advanced 3D-printers and to adopt a wide range of materials. Therefore, as fabricators under Model

B.1 only accomplish the fabrication process but do not contribute new concepts, Model B.1, to some extent, is driven by scale. As a result, there is intense competition between fabricators under Model B.1.

The most significant impact of the competitive market under Model B.1 is that the price mechanism and warranties become important signals to indicate to consumers the risk of producers' behaviour. Under Model B.1, a fabricator is usually motivated to provide warranties voluntarily. In practice, most fabricators limit their warranties to the extent of the fabrication activities that are possible with state-of-the-art technologies. For instance, *Shapeways* writes clearly in its warranties:

> *"Shapeways warrants only that the model manufactured by us will substantially meet the features of the indicated 3D Model within the limitations of the 3D printing technology. **You maintain sole legal responsibility for the design specifications and performance of the 3D Model that is the subject of this transaction**."*[300]

In addition, taking *Stratasys Direct* as an example, a lot of other factors that can be difficult to control by the fabricator are excluded from the scope of warranties:

> *"Stratasys Direct Manufacturing makes no representations, warranties, guarantees or conditions as to materials, strength, tolerances, or other Part characteristics."*[301]

[300] Section 4 of the Terms and Conditions offered by the Shapeways. Available at: https://www.shapeways.com/terms_and_conditions. Visited on June 6th, 2019.

[301] Section 14 of the Stratasys Direct Terms and Conditions. Available at: https://www.stratasysdirect.com/company/legal-terms. Visited on June 6th, 2019.

In practice, some fabricators also like to guarantee the safety of their products by claiming that the product complies with specific safety standards[302] or by providing an instant quote service that includes informing the CAD file holder about potential risks with the file.[303]

The warranties voluntarily offered by fabricators with Model B.1 have critical implications in terms of deterrence and risk-shifting. On the one hand, fabricators are incentivised to increase the level of precaution to the extent that is promised in the contract. On the other hand, as the fabricators under Model B.1 mostly are professional SMEs, by providing warranties, risk is expected to be shifted from the more risk-averse consumers to the less risk-averse fabricators, which implies an increase of social welfare.

5.2.2. Contracting over the risk associated with physical fabrication under Model B.2

The business under Model B.1 in practice connects professional fabricators with the consumers who usually have high requirements for the function and performance of a product. While a high level of safety might be promised by the fabricator as offering warranties voluntarily, the fabricator under Model B.1 may not be ultimately chosen by the consumer.

In practice, for several reasons, the consumer may turn to a printing hub under Model B.2 rather than visit a professional fabrication platform that runs a business as Model B.1. Firstly, if the product to be fabricated is a simple one, which is for household, not industrial purposes, the fact that stringent mechanical performance may not be required implies that the consumer can simply rely on a desktop-level 3D printer. Also, compared to Model B.1, fabrication under Model B.2 is less costly and more flexible. A consumer can quickly find a nearby 3D hub from an online marketplace (e.g. *Treatstock*) and the final product could be delivered to in a short time.

Several problems confronting consumers under Model B.2 may prevent them from reaching an agreement that provides fabricators with the optimal incentive and shifts risk in advance. Firstly,

[302] For example, Sculpteo guarantees in its terms that "SCULPTEO provides its CUSTOMERS with a guarantee that the OBJECTS are manufactured in France, in accordance with French legislation and the applicable French quality and safety standards." See IX(9)(i) of the Sculpteo General Terms and Conditions, available at: https://www.sculpteo.com/en/terms/. Visited on June 8th, 2019.

[303] The service of the instant quote can be seen at SD3D, available at: https://quote.sd3d.com/en/Order3DPrint. Visited on June 8th, 2019.

fabricators under Model B.2 are mostly non-professional individuals. Compared with the SMEs who operate a business under Model B.1, these non-professionals are less capable of producing sufficient information. What is worse, consumers are unable to coordinate the project with the fabricators under Model B.2 as comprehensive as that under Model B.1. It determines that safety information may not be fully understood by consumers. As a result, the existence of information asymmetry under Model B.2 implies that some risks that should not have been internalised by consumers are not allocated in the contract. Consumers that are not the parties to efficiently deal with these risks have to bear these risks, while the parties that should have been provided with the incentive are free of taking measures.

In addition, the problem of risk-shifting may also be present under Model B.2. Unlike fabricators under Model B.1, who are SMEs with decent capacities, fabricators under Model B.2 are mostly ordinary individuals that show a slight difference with consumers in terms of risk-aversion. Therefore, the fabricator is unwilling to include a clause on risk-shifting. To explain, factors such as uncertainty about the correlation between technical specifications and probability of damage, risk-aversion, potential insolvency, as well as incomplete competition, prevent an ordinary individual fabricator from voluntarily offering warranties. Also, as the behaviour of consumers becomes more of a determinant of the risk in the final product, the fabricator is reluctant to provide warranties if it can do little to differentiate consumers or monitor their post-sale behaviour.

5.2.3. Contracting over the risk associated with physical fabrication under Model B.3

Unlike Model B.1 and Model B.2, in which a fabricator and a consumer can conclude a contract directly, under Model B.3, the fabricator and the consumer are connected by an intermediary (the so-called "agent-platform", e.g. *3D Hubs* and *Xometry*).[304] In this scenario, a chain of contracts is formed, even though it only contains three parties. The consumer firstly concludes a contract with the agent-platform. After receiving the CAD file and testing its printability, the agent-platform will further conclude a contract with a fabricator from its pool. After the fabricator completes the physical object, it will send the object to the agent-platform, which will inspect it against a checklist before sending it to the consumer.

[304] See Twigg-Flesner (2015), supra note 291, at 55.

As noted before, production is democratised with 3D printing; this means that producers are scattered around the world. Without a linear supply chain, a consumer has to make a considerable effort to meet a fabricator and has to gain information to specify the qualification of the fabricator. This problem, however, could be alleviated with the help of agent-platforms in Model B.3.

Firstly, the emergence of agent-platforms reduces the transaction cost between supply and demand. For consumers who are looking for a fabricator with a specific capacity, if the service fee asked by the agent-platform is significantly lower than what they would spend searching for a fabricator, consumers would prefer to employ an agent-platform. In practice, agent-platforms establish their business by focusing on developing extensive partnerships with a vast number of certified fabricators. These fabricators operate different kinds of 3D printers and they are specialised in different skills. Therefore, by holding such a massive pool of fabricators, the agent-platform can, to a significant extent, promote the connection between demand and supply.

Secondly, an agent-platform serves as a signal for product safety. In order to establish a partnership with the agent-platform, a fabricator has to meet all the qualifications that are required by the platform. For example, in order to cooperate with *3D Hubs*, a fabricator has to prove that: (1) it has got a certification from an authorised body; (2) its printers are of a high standard; (3) it will not outsource any process to others. In this regard, one of the most significant contributions of the agent-platform is that it serves as the governor and establishes a "club" to control the service of fabrication, which is of the nature of a public good. Compared to other business models, the consumer can reasonably believe that the safety level of the fabricators chosen by the agent-platform is above average.

Model B.3 incentivises fabricators to behave appropriately. Fabricators that run a business with Model B.3 are induced to behave appropriately because of the governance by the agent-platform. In order to join the "club" operated by the agent-platform, some safety provisions are already included in the contract between the platform and the fabricator. If the fabricator does not meet the criteria required by the agent-platform, it will be differentiated from safe fabricators and thus will not be authorised to build a business partnership with the platform. In other words, the adverse selection problem can be significantly overcome at this stage. In addition, once running a business on the platform, the incentive for the fabricator to behave appropriately will not diminish because otherwise it would be punished by the operator of the platform or even suspended from offering printing service in platform. However, it should be noted that, in Model B.3, whether the fabricator can be induced to optimise its behaviour depends on whether the agent-platform can observe this optimal level. *In this regard, the fabricator has no incentive to take additional precautions beyond the requirement of the agent-platform***.** The optimal care level can be adopted by the fabricator, only if this criterion is accurately identified by the agent-platform.

This quality control will be further reflected and guaranteed in the contract concluded by the consumer and the agent-platform. Firstly, an agent-platform guarantees that all its fabrication partners are certified to various standards.[305] Secondly, the agent-platform promises that it will inspect the product to the extent that it is built to the consumer's specification. For example, *Xometry* guarantees that in the process of fabrication, key information and documents will be thoroughly communicated to the consumer.[306]

In addition, the active engagement of the intermediary platform also has a great implication for risk-shifting. Unlike Model B.1 and Model B.2, in which risk-shifting is largely dependent upon the capacity of contractual parties, the pool of fabricators operated the intermediary platform indicates that risk can be spread among a large number of participants. Therefore, even if the fabricators are risk-averse in essence, they may further spread with the help of the intermediary platform.

5.2.4. Summary

After obtaining the CAD file, under the "separation" model, the consumer has to find a fabricator to print out the final product. However, due to the variance of business model that a fabricator comes from, s/he could be provided with different incentives from the contractual relations. From the perspective of deterrence, fabricators under Model B.2 are least incentivised to behave appropriately. In comparison, a significant improvement is witnessed under Model B.1 and Model B.3. From the perspective of risk-shifting, since both contractual parties are risk-averse under Model B.2, they may not find a way of shifting risk through contracts. Risk-averse consumers may

[305] For example, the agent-platform *Xometry* guarantees that all the partners undertaking fabrications have the certifications like ITAR, AS9100, ISO 9001, ISO 13485, UL, ISO 7 & 8 Medical Clean Room or NADCAP.

[306] The typical incidents that would be offered by *Xometry* are design feature confirmation, tolerance confirmation and key quality documents.

shift risk through contracts under Model B.1. By shifting the risk from more risk-averse consumers to less risk-averse SMEs, social welfare is expected to increase to some extent. It indicates that social welfare will continue to increase, provided that SMEs can further shift the risk. By introducing an intermediary platform, Model B.3 shows potential to further spread the risk among a pool consisting of numerous fabricators.

5.3. Chapter conclusion

In the era of 3D printing, a typical production process is characterised as a "separation" model, in which the CAD file and the final product are respectively accomplished by the parties from different entities. It is the consumer that acts to coordinate the production process by reaching agreements separately with these involved parties. This section discusses the issue of whether social welfare can be maximised under such a "separation" model. That is, whether contracts can provide the involved parties with the optimal incentive in a specific business model and whether the risk-averse parties have to bear the risk in the end. The analysis above indicates that the effect of contracts shows a great difference among different business models.

Assuming that the consumer confronts low cost to bargain with the digital designer and the fabricator and that s/he has sufficient information to accurately determine the full price of the product, it is expected that contractual relationship could provide relevant parties with the optimal incentive. What is more, if digital designers and fabricators are risk-neutral, risk-averse consumers are able to shift risk in advance. In this ideal scenario, optimal social welfare can be achieved through the two contracts. However, as analysed in Section 5.1 and 5.2, the present barriers of bargaining and the information asymmetry between contractual parties imply that consumers may have to internalise some costs that should have been borne by digital designers and fabricators. As a result, relevant actors may not be incentivised to behave optimally. What is worse, as digital designers and fabricators are risk-averse under specific business models, consumers may be unable to shift the risk through contracts.

The extent to which factors like transaction cost, information problem or risk-aversion emerge to diminish social welfare under various business models are summarised in Table 6 as below. By combining the business models under Model A and Model B in different ways, the effect on deterrence and risk-shifting would also be in large divergence.

Table 6: Contracting over product risk under various business models in 3D printing

Separation models	Sub-models	The level of transaction cost	The level of Information problem	The possibility of risk-shifting	Is there an intermediary platform?
Digital designing	Model A.1	High	High	No	Yes
	Model A.2	High	High	No	Yes
	Model A.3	Low	Low	Yes	No
Physical fabrication	Model B.1	Low	Low	Yes	No
	Model B.2	High	High	No	Yes
	Model B.3	Low	Low	Yes	Yes

Implications for deterrence

According to Table 6, under particular business models (i.e. Model A.3, Model B.1 and Model B.3), CAD file designers and fabricators are better incentivised to behave appropriately. In contrast, the effect on deterrence turns to be worse if consumers rest on other business models (i.e. Model A.1, Model A.2 and Model B.2) to accomplish the final product.

In practice, consumer is the party that has to coordinate the process of risk allocation through contracts. As shown in Table 7 as below, a consumer has to obtain the CAD file from one of the three business models in the *left column*, and then takes it to a fabricator who offers printing service in one of three business models in the *right column*. Therefore, how a consumer combines Model A with Model B has a great impact on the effect on deterrence and risk-shifting.

Table 7: Different combinations under the "separation model"

Digital modelling		Physical fabrication
Model A.1	consumers	Model B.1
Model A.2		Model B.2
Model A.3		Model B.3

In general, three types of combination can be made by consumers, which could result in quite different effects on deterrence.

Firstly, According to Table 6, the transaction cost and information asymmetry are less severe under Model A.3, Model B.1 and Model B.3. In this regard, provided that consumers choose to obtain CAD files via Model A.3 and then contact with fabricators who operate business under Model B.1 and Model B.3, contracting over product risk is expected to provide both CAD file designers and fabricators with a decent incentive to behave appropriately.

Secondly, the deterrence effect is distorted in the case that the consumer confronts prohibitive transaction cost and information asymmetry in the course of bargaining over the product risk with the CAD file designer or the fabricator. Two scenarios are distinguished. If a consumer opts for a CAD file from a professional under Model A.3, but later finds a non-professional fabricator from the online marketplace (e.g. using Model B.2), s/he may expect that some of the risk occurred in the course of printing is not included into the contract with the non-professional fabricator. Likewise, a consumer may choose a CAD file from non-professional sources (e.g. under Model A.1 or Model A.2) and then take it to a professional printer (e.g. under Model B.1 or Model B.3).

If this is the case, some of the risk posed by the CAD file designer may not be concluded into the contract, which will inaccurately be internalised by the consumer.

At last, if a consumer chooses to acquire a CAD file from a non-professional designer (e.g. under Model A.1 or Model A.2) and then takes it to another non-professional fabricator (e.g. under Model B.2), compared with other combinations abovementioned, the consumer may confront more transaction costs and/or information asymmetries. As a result, the consumer is at a higher risk of bearing the cost which should have been internalised by the CAD file designer and the fabricator through the contract separately concluded with them.

Implications for risk-shifting

The socially optimal outcome is not only influenced by the deterrence effect offered to the involved parties, but it also rests on the issue of whether risk-averse parties have to bear the risk in the end. Compared with traditional mass producers, the parties that engage in 3D printing activities are less capable of resisting product risk. In particular, as we found in different business models (i.e., Model A.1, Model A.2 and Model B.2), CAD file makers or fabricators are individuals, who show no significant difference from ordinary people. In this regard, if a consumer decides to acquire a CAD file from Model A.1 and Model A.2, and then s/he takes to an individual fabricator under Model B.2, there is no party along the supply chain who is significantly less risk-averse than others.

In comparison, if the consumer seeks for a CAD file under Model A.3 and/or prints it out by a fabricator under Model B.1, it seems that at least one party from the supply chain is less risk-averse than the consumer. In this latter scenario, by adding the relevant cost into the price, risk-shifting is possible from the consumer to the less risk-averse actor. As a result, an increase of social welfare is expected to be achieved.

However, it should be noted that the aforementioned risk-shifting is based on another two assumptions. On the one hand, the seller is absolutely risk-neutral, meaning that bearing the risk in the end or shifting it in advance makes no difference to the seller. On the other hand, the digital designer and/or fabricator suffer no information asymmetry, so that they can accurately assess the risk posed by the consumer. Such assumptions may not hold under Model A.3 and Model B.1. To explain, while the SMEs are less risk-averse than consumers, they are still risk-averse parties.

Therefore, SMEs may still seek for further risk-shifting after taking over the risk from consumers. Within the contractual relationship in Model A.3 and Model B.1, since the party that is even less risk-averse is not observed along the chain of contracts, it seems that contractual relationship cannot help further shifting the risk borne by SMEs. What is worse, the seller may not precisely decide the risk to be added into the price due the presence of moral hazard. Consequently, considering that the SMEs who run business under Model A.3 and Model B.1 may still be risk-averse and the potential moral hazard problem, contractual relationship alone may not achieve the goal of risk-shifting even in the scenarios it in theory promises to do so.

The analysis in this Chapter further implies the promising role of Model B.3 with respect to improving the risk-shifting problem. As the party who concludes a contract with the consumer for printing service, the intermediary platform is able to firstly shift the risk from the consumer to it and then spread it through all the fabricators who run business on the platform.

To summarise, the contractual relation in reality does not ensure that risk could smoothly shift from the risk-averse parties to risk neutral ones. To further improve risk-shifting in the “separation model”, additional risk-shifting instruments should be provided to risk-averse parties to shift the risk where contractual relationship fails to do so. What is more, signalling instruments should also be developed to remove the information asymmetry that prevents sellers from offering coverage wherever risk-shifting is possible through contracts.

Conclusions

In theory, given specific conditions (e.g. transaction costs, information problems), the analysis in Chapter 4 indicates that bargaining over product risk could result in a socially optimal outcome. This proposition poses no difference to separation models in the context of 3D printing where digital designers and fabricators are strangers to each other, provided that the agreements that the consumer separately conclude with the digital designer and fabricator can provide each of them the optimal level of deterrence.

However, according to the analysis in Chapter 5, digital designers and fabricators may not be incentivised to behave efficiently, because the present transaction cost and information asymmetry in specific scenarios would prevent parties from efficiently bargaining over the risk. This deviation from efficient deterrence is more severe in some business models (e.g. in Model A.1, Model A.2 and Model B.2) than in the others (e.g. in Model A.3, Model B.1 and Model B.3). As a result, if a consumer chooses to coordinate the process of production by relying on Model A.1, Model A.2 and Model B.2 more than Model A.3, Model B.1 and Model B.3, more risks that should have been internalised by digital designers or fabricators would ultimately be allocated to consumers. Even in the business models that we expect a better deterrence effect can be resulted (i.e. Model A.3, Model B.1 and Model B.3), as consumers may not observe the optimal activity level of CAD file makers and fabricators, these parties would be incentivised to take precautionary measures only to the extent that can be observed by consumers. Therefore, additional instruments are desirable to correct the deterrence effect, especially in the business models where digital designers and fabricators are less incentivised to behave appropriately.

In addition to deterrence issue, risk-shifting serves as another factor that has an impact on social welfare. The law and economics theory explains that risk-shifting would not influence social welfare provided that consumers are able to shift the risk to risk-neutral parties along the supply chain. The analysis in Chapter 5, however, contradicts to this assumption. The fact that sellers under specific business models (e.g. Model A.1, Model A.2 and Model B.2) are not obviously less risk-averse than consumers implies that consumer may not shift risk at all through contracts under these scenarios. Apart from that, while sellers under Model A.3 and Model B.1 are less risk-averse than consumers, they may still have a motive of risk-shifting after taking over the risk form the consumer. Worse still, the existence of information asymmetry between the seller and the consumer may serve as another factor discouraging the seller from offering the coverage. Several important points in terms of risk-shifting under separation models could be concluded. Firstly, additional risk-shifting instruments are desirable, especially in the business models where parties cannot reach an agreement on risk-shifting. Secondly, in the circumstances where risk-shifting is possible, additional measures on reducing information asymmetry should be developed. Last but not the least, online platform may play an increasing important role in terms of risk-shifting.

Having examined the extent to which contracting over product risk under separation models may fail to result in the optimal deterrence and may not lead the risk-averse consumers to shift the risk, the following discussion in this research will continue to explore whether other instruments could provide the involved parties with extra incentives to behave appropriately and help the risk-averse consumers to shift risk in concrete scenarios. The performance of the tort liability regime is firstly explored in the next part, and in Part IV, other complementary instruments such as regulations and platform governance are examined.

PART III

DETERRENCE AND RISK-SHIFTING IN THE CONTEXT OF 3D PRINTING THROUGH THE LENS OF TORT LIABILITY

Introduction

Part II discussed the possibility of using the contractual relation to achieve the goals of deterrence and risk-shifting. According to the analysis in Part II, contracting over product risk plays an important role in deterrence and risk-spreading. Given several key assumptions, liability rules or statutory interventions are not necessary, because people would always to incentivised to reallocate risks and obligations to pursue the socially optimal outcome. However, as we found previously, the socially optimal outcome can be achieved only if the relevant parties have a chance to reach an agreement and they can correctly perceive the relevant information. In the context of 3D printing, the analysis in Part II shed light on that contractual liability has the potential to provide contractual parties with an incentive to take measures up to the observable level. However, this deterrence effect could be distorted if production is organised under specific business models (e.g. Model A.1, Model A.2 and Model B.2). What is worse, as relevant parties are more risk-averse than traditional producers, risk-spreading could be problematic as well. The preliminary conclusion drawn from Part II is that relevant parties should be offered additional incentives to behave appropriately and be provided with approaches to spread risk when necessary.

Against this background, the analysis in this part shifts to another legal instrument that is widely used for allocating the risk: tort liability. The main interest in Part III is to examine the extent to which liability rules could achieve the goals of deterrence and risk-shifting in the context of 3D printing.

The structure of this part proceeds as follows. Chapter 6 outlines the evolution of product liability and it shows that an expansion of extra-contractual liability has been driven by disruptive technologies. It is found that conventional criteria, which are used to decide whether tort liability should be extended to new product risk and which kind of liability rules should be adopted, no longer provide a convincing and stable framework for analysing the separation models in the context of 3D printing. Chapter 7 indicates that the insights from the law and economics can help us delineate the extent to which one specific liability rule is preferable to another. The analysis in this chapter will pay closer attention to the issue of whether strict liability should apply to CAD file designers and fabricators. Chapter 8 further analyses the impact of the tort liability on the socially optimal outcome from the perspective of risk-shifting.

Chapter 6. Product Liability at the Crossroads of 3D Printing: A Positive Legal Analysis

After the Industrial Revolution, due to the development of productivity and transportation, producers are able to send their products to every corner of the world. To ensure that the safe products are placed in circulation, various tort liability rules were developed. Especially, the regime of strict product liability has been established around the world. In practice, as the digitalisation keeps disrupting the process of production, ambiguities appear in the application of strict liability. Later, the debate on clarifying these ambiguities among the Member States results in different approaches in applying tort liability to deal with product risk in the digital age.

The main interest of this chapter is twofold. Firstly, it has a brief retrospect of the development of product liability in legal practice. Secondly, it sheds lights on the controversy of applying strict liability in the digital age. This chapter conducts a positive legal analysis, the aim of which is to clarify the potential liability borne by specific parties in the context of 3D printing. Later, in Chapter 7 and 8, the efficiency of specific liability rules in the context of 3D printing will be assessed.

6.1. Product liability in the early stage: the US perspective

For a long time, the way to tackle product risk in the US was consistent with the rule of privity and the theory of warranties. This doctrinal approach was transformed from the start of the twentieth century. The following discussion briefly describes the history of how strict product liability gradually replaced this old contract-based approach.

6.1.1. From privity of contract to strict liability: a case-law driven transformation in the US

In the case *Winterbottom v. Wright*[307], the privity rule protected a producer from a claim by a non-contractual party. At the time, when damage was caused by a product, a victim who had no contractual relationship with the producer could not claim against the producer even if the damage was caused by the negligence of the producer. The only way that a non-contractual party could recover the damage caused by a product was the case where the producer expressly assumed liability in product warranties.[308] As a result, a rule of *caveat emptor*[309] de facto dominated cases relating to product risk for a long time.[310] Implied warranty was proposed to remedy the problems under *caveat emptor* in the nineteenth century, in which circumstances, a producer warranted that no hidden defects existed. However, the adoption of the implied warranty was still constrained by privity to some extent. If the plaintiff lacked privity, which means that s/he was not an actual purchaser, his/her claim against the producer would be rejected because the warranty only implied that the product was fit for the "buyer's" purpose.[311]

The problem with the rule of privity amounted to under-deterrence and under-compensation since mass production substantially disrupted the direct contractual relationship between the producer and consumer. The producer would not be incentivised to behave optimally, and the consumer could no longer fully recover in this scenario. As a result, on the one hand, the producer was motivated to lower its care level and more unsafe products were thus placed in the market; on the other hand, the consumer became hesitant to purchase unfamiliar products. Confronted with the problems, judges reversed the rule in dealing with product risk via some landmark cases.

[307] See *Winterbottom v Wright* (1842) 10 M&W 109.

[308] See Owen, David G. "The evolution of products liability law." Rev. Litig. 26 (2007): 955.

[309] Caveat emptor means "let the buyer beware". Its history can date back to old English law. See Buchanan, James M. "In defense of caveat emptor." The University of Chicago Law Review 38, no. 1 (1970): 64-73.

[310] According to literature, in the US, the principle of caveat emptor persisted in most states in the early twentieth century. See Owen (2007), supra note 308, at 962.

[311] Prosser, W. L. (1943). The implied warranty of merchantable quality. Can. B. Rev., 21, 446.

MacPherson v. Buick Motor Co. (1916)

In the case *MacPherson v. Buick Motor Co.*[312], the plaintiff MacPherson was injured when driving the car due to the collapse of its wheels. Instead of suing the dealer from whom he bought the car, MacPherson sued the producer *Buick* directly. Judge Cardozo supported the claim from MacPherson by refusing to abide by the rule of privity. He gave his explanation by embracing the rule of negligence. Judge Cardozo expressed in the verdict that "irrespective of contract, the manufacturer of this thing of danger is under a duty to make it carefully... If he [the producer] is negligent, where danger is to be foreseen, a liability will follow."[313] In the aftermath of the case, if no disclaimer was found in warranties, the rule of negligence could be used by consumers in the circumstances where they had no contractual relationship with the producer. In brief, the importance of the MacPherson case is that the paradigm of product liability shifted from the (contractual-based) privity to the (tort-based) negligence rule.[314]

Escola v. Coca Cola Bottling Co. (1944)

Twenty-eight years after the case MacPherson, another landmark case was *Escola v. Coca Cola Bottling Co.,*[315] and Justice Traynor's decision marked a further significant shift from negligence to strict liability in dealing with accidents caused by defective products.

Ms Escola was a waitress who was injured by the explosion of a Coca Cola bottle. Justice Traynor from the Supreme Court of California favoured the claim by Escola based on the doctrine of *res ipsa loquitur*, in which sense the victim did not need to prove the negligence of the producer. According to Justice Traynor, it should be in no doubt that a manufacturer incurs an absolute liability "when an article that he has placed on the market, knowing that it is to be used without an inspection, proves to have a defect that causes injury to human beings."[316] In this situation, as

[312] MacPherson v. Buick Moter Co. 111 N.E. 1050, 217 N.Y. 382.

[313] See *MacPherson*, supra note 312, at N.Y. 384 and 389.

[314] Croley, Steven P., and Jon D. Hanson. "Rescuing the revolution: The revived case for enterprise liability." Michigan Law Review 91, no. 4 (1993): 683-797.

[315] Escola v. Coca Cola Bottling Co. 24 Cal.2d 453, 150 P.2d 436.

[316] See *Escola*, supra note 315, 24 Cal.2d 462.

proving the negligence of the producer was unnecessary, Justice Traynor was actually advocating the imposition of strict liability on producers.

Henningsen v. Bloomfield Motors (1960) **and** ***Greenman v. Yuba Power Products, Inc. (1963)***

In the first case, Mr Henningsen bought a car for his wife, who was seriously injured ten days later when the steering failed and the car ran into the wall. A disclaimer of implied or express warranties on any party other than the purchaser was embedded in the warranty.[317] This clause implied two points. Firstly, the damage caused by the product should respect privity, meaning that any party other than the actual buyer had no right to claim against the producer under the theory of warranty. Secondly, an implied warranty could be evaded via an express warranty concluded by the producer and the consumer. These two points, however, were rejected by Justice Francis. His core argument was that an implied warranty of merchantability was based fundamentally on tort liability and not on a contractual relationship.[318] In this regard, *Henningsen* confirmed that product risk should be fundamentally decided and allocated through strict liability rather than contractual terms.[319] The essence of the *Henningsen* was meanwhile reflected in academia. For example, Prosser was in favour of piercing the mask of contract law in product liability in his famous article, stating that "if there is to be strict liability in tort… let there be strict liability in tort, declared outright, without an illusory contract mask."[320]

The wisdom contained in the case *Henningsen* was again anchored by Justice Traynor in the case *Greenman v. Yuda Power Products, Inc.*[321] three years later. He cited and summarised the opinions in *Escola* and *Henningsen* as well as the idea from precursors of strict product liability in the

[317] The contract concluded by Mr. Henningsen contained the following clause. "This warranty being expressly in lieu of all other warranties expressed or implied, and all other obligations or liabilities on its part, and it neither assumes nor authorizes any other person to assume for it any other liability in connection with the sale of its vehicles." See Henningsen v. Bloomfield Motors. 161 A.2d 69 (N.J. 1960).

[318] In the verdict, Justice Francis articulated that the claim from the buyer and other people should not depend upon the "intricacies of the law of sales". See supra note 317.

[319] Priest, George L. "The invention of enterprise liability: a critical history of the intellectual foundations of modern tort law." The Journal of Legal Studies 14, no. 3 (1985): 461-527.

[320] See Prosser, W. L. (1960). The assault upon the citadel (strict liability to the consumer). Yale Lj, 69, 1099.

[321] Greenman v. Yuda Power Products, Inc. 377 P.2d 897 (Cal. 1963).

verdict. In particular, he wrote that "the abandonment of the requirement of a contract between them [i.e. the producer and the consumer], the recognition that the liability is not assumed by agreement but imposed by law, and the refusal to permit the manufacturer to define the scope of its own responsibility for defective products *make clear that the liability is not one governed by the law of contract warranties but by the law of strict liability in tort*."[322]

These typical cases placed product risk under the shelter of strict liability, and this tendency swept the US in the succeeding years.[323] From personal injury to property damage, from the direct purchaser to its employees as well as other bystanders, the country witnessed a significant expansion of strict product liability.

6.1.2. Product liability in the Restatements in the US

The expansion of strict product liability in case law quickly led the American Law Institute (ALI) to formulate consensus principles in the *Restatement (Second) of Torts*[324] in 1965.[325] According to Section 402A, a commercial seller is liable, if its product sold was "in a defective condition unreasonably dangerous" at the time of sale and it caused physical harm.[326] It is stressed within Section 402A that the liability on the commercial seller holds even in the situation where the commercial seller has exercised all possible care and where the victim has entered into a contractual relationship with the seller.[327] In this regard, Section 402A clearly makes the commercial seller of defective products strictly liable, and the existence of a contract cannot override this strict liability.

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[322] See *Greenman*, supra note 321, 377 P.2d at 901.

[323] Prosser, William L. "The Fall of the Citadel (Strict Liability to the Consumer)." Minn. L. Rev. 50 (1965): 791.

[324] American Law Institute, RESTATEMENT (SECOND) OF TORTS § 402A (1965).

[325] Documented in literature, the revision work led by the ALI can date back to the late 1950s. At that time, the initial intent of the ALI was to apply the rule of negligence as the standard of product liability. However, prompted by the iconic case like *Henningsen* (1960) and *Greenman* (1963), which were settled down during the period of revision, the adopted principle was simultaneously changed. See Owen (2007), supra note 308, at 974-975.

[326] See Owen (2007), supra note 308, at 974-975.

[327] See ALI, supra note 324, Section (2)a and 2(b).

After the promulgation of Section 402A, different states across the US started to transplant its principle into their own jurisdictions. In the middle of the 1970s, forty-one of fifty jurisdictions adopted strict liability as the standard to deal with an accident caused by defective products.[328]

The expansion of strict liability reached its apex by 1980. Some unexpected incidents in practice after that, however, stimulated lawyers to rethink the entrenchment of strict product liability. By the 1990s, as courts had accumulated tremendous experience on disputes over defective products, they agreed that product defects could be divided into three categories: manufacturing defect, design defect and insufficient warning. While a strict product liability was widely accepted in different states, "it has been an open secret that courts… in fact have been applying principles that look remarkably like negligence [to the accidents caused by design defects and insufficient warnings]."[329] The situation that many states did not apply strict liability to the design defects and insufficient warning motivated the ALI to re-evaluate the strict product liability standard set by Section 402A. The *Restatement (Third) of Torts: Products Liability* (the "Product Liability Restatement")[330] was thus published against this background in 1998. In this version, the standard of liability rules applicable to product defects featured a functional approach, which means that the focus of the rule was no longer on the distinction between strict liability and negligence but on the issue of how courts actually apply these rules in practice to settle the disputes. In this way, the three kinds of product defect were distinguished and different criteria were offered to assess them.

In particular, while an accident caused by a manufacturing defect is determined by the expectation of consumers, the accident caused by a design defect or insufficient warning is determined under a risk-utility trade-off. Therefore, the producer would be liable, "if the foreseeable risk of harm posed by the product could have been reduced or avoided by the adoption of a reasonable alternative design", or "if the foreseeable risk of harm posed by the product could have been reduced or avoided by the provision of reasonable instructions or warnings."[331] According to the reporters of the Product Liability Restatement, while a functional approach was adopted to single

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[328] Priest (1985), supra note 319, at 518.

[329] See Owen (2007), supra note 308, at 988. See also Henderson Jr, James A., and Aaron D. Twerski. "Doctrinal collapse in products liability: The empty shell of failure to warn." NYUL Rev. 65 (1990): 265.

[330] American Law Institute, The Restatement (Third) of Torts: Products Liability (1998).

[331] See ALI, supra note 330, Section 2(b) and 2(c).

out the liability for design defects and insufficient warnings, the grounding could still be categorised as a fault-based liability.[332] In this sense, a producer is considered negligent if it failed to adopt a reasonable alternative design or instruction at the time of production.

6.1.3. Summary

To summarise, two remarkable stages can be distinguished in the evolution of product liability in the US. In the initial stage, starting from the early twentieth century, the rule based on contractual terms and the theory of warranties was gradually replaced by the rule of negligence which was, in turn, replaced by strict product liability.[333] As courts had ample experience in deciding cases relating to modern production, they found that imposing the duty on the producer to warn of unforeseeable risks or to design without unforeseeable risk was extremely stringent. Therefore, since the 1980s, the standard adopted for design defects and insufficient warning steadily fell into the rule of negligence.

6.2. The adoption of strict product liability in Europe

While strict liability was applied in the US, on the other side of Atlantic, an accident caused by defective products was still handled through contract law (sales law) and general negligence rules.[334] However, what took place in the US had a massive impact on the evolution of the regime of product liability in jurisdictions worldwide in the following years. This subsection briefly reviews how the current product liability regime across the European Union was established and, more importantly, it highlights the key provisions and shows how they were transplanted in the Member States.

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[332] Twerski, Aaron D. "Chasing the illusory pot of gold at the end of the rainbow: Negligence and strict liability in design defect litigation." Marq. L. Rev. 90 (2006): 7. See also Cupp Jr, Richard L., and Danielle Polage. "The Rhetoric of Strict Products Liability Versus Negligence: An Empirical Analysis." NYUL rev. 77 (2002): 874; Owen, David G. "Design Defects." Mo. L. Rev. 73 (2008): 291.

[333] Owen, David G. "Rethinking the Policies of Strict Products Liability." Vand. L. Rev. 33 (1980): 681.

[334] Greer, Thomas V. "Product liability in the European Community: the legislative history." Journal of consumer affairs 26, no. 1 (1992): 159-176. See also Van Wasse van Gatwijck, Otto baron. "Products Liability in Europe." Am. J. Comp. L. 34 (1986): 789.

6.2.1. The background of the European Product Liability Directive

In Europe, as the scope of mass production grew, the legal regime concerning accidents caused by product defects witnessed a significant dilution of the privity of contract. In sales law, an array of measures that enable the final buyer to claim against any upstream party along the chain of contracts have been adopted by the Member States to eliminate the constraint of privity. Apart from that, a revolution also meanwhile occurred to the sphere of tort law. A producer has the duty of care for any user of the product without reference to contractual ties.[335] In Germany, the burden of proof was reversed from the consumer to the producer in the so-called Fowl Pest Case in 1968. Since that time, the presumption of negligence could be rebutted on a case-by-case basis.[336] Further, in 1976, a special Drag Act even introduced strict liability in Germany and also served as the first product liability law in Europe.[337] As a result, the different attitudes to consumer protection among the Member States led them to take different approaches to product liability.

This divergence led to severe problems at the level of consumer protection across Europe. For example, in the jurisdictions where a consumer was able to claim against the producer directly, such as in France through the regime of a direct claim under sales law[338] and in Germany through strict liability like the 1976 Drag Act under tort law, the producer had to pay a large insurance premium.[339] In comparison, a similar producer in other jurisdictions like Italy would not have to pay this amount. As a result, the different regimes for product liability were actually regarded as distorting competition in Europe.[340]

[335] See Greer (1992), supra note 334, at 164.

[336] See BGH, Urt. v. 26.11.1968 (Fowl Pest Case), BGHZ 51, 91 (102).

[337] See Gesetz fiber den Verkehr mit Arzneimitteln [Arzneimittelgesetz] v. 24.8.1976 (BGB1. I S. 2445).

[338] In France, a specific regime called the action directe en garantie applies, which presumes that "each purchase who resells the goods also sells his claims against the seller". Therefore, "the final purchaser has the right to immediately direct his guarantee claims against the producer or one of the other sellers in the chain of contracts." See Ebers and Meyer (2009), supra note 234, at 11.

[339] Taschner, Hans Claudius. "Harmonization of products liability law in the European Community." Tex. Int'l LJ 34 (1999): 21.

[340] Reimann, Mathias. "Liability for defective products at the beginning of the twenty-first century: Emergence of a worldwide standard." Am. J. Comp. L. 51 (2003): 751.

Confronted with this situation, Member States gradually recognised the necessity of harmonising product liability across Europe, and this motive was stimulated by events from the late 1960s.[341] Subsequently, the Commission of the European Economic Community (EEC) proposed a directive to approximate the laws on product liability in 1976. In the same year, the Commission submitted a draft directive, in which a liability rule based on no-fault was proposed for personal injury and material damage caused by defective products.[342] After years of debate, the final version of the European Product Liability Directive (the "EPLD")[343] was ultimately adopted by the Council of Ministers in 1985.

6.2.2. An overview of the EPLD

As mentioned in the preamble of the EPLD, two major points explain the necessity of issuing the directive. On the one hand, the directive aims at preventing the distortion of competition in the realm of production across the community, as a result of which the free movement of goods could be ensured. On the other hand, increasing the level of consumer protection serves as another important goal of the directive.[344]

The outstanding feature of the EPLD is that a no-fault liability rule is formally established in the EU. In general, the producer shall take the liability for the damage caused by a defect in its product, no matter whether the producer is diligent or not.[345] In this sense, while the directive clearly shows a pro-consumer attitude, it also advocates fair risk allocation consistent with modern technological

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[341] According to literature, at least three multinational events provoked the movement toward harmonization of product liability in Europe. The first one took place in the Hague Conference on Private International Law. The Hague Conference aimed to tackle the problems relating to the conflicts of law, and it included all the E.C. members. In 1967, the U.S. representative articulated the importance of uniformed product liability during the conference. This argument firstly drew attention in Europe. The second was the so-called Strasbourg Convention drafted by the Council of Europe. This convention was regarded as pro-consumer by expressing better protection than national laws back then. The third event was the Paris Summit, in which a program focusing on consumer affairs was initiated. See Greer (1992), supra note 334; Reese, Willis LM. "Further Comments on the Hague Convention on the Law Applicable to Products Liability." Ga. J. Int'l & Comp. L. 8 (1978): 311.

[342] See Van Wasse van Gatwijck (1986), supra note 334.

[343] COUNCIL DIRECTIVE of 25 July 1985 on the approximation of the laws, regulations and administrative provisions of the Member States concerning liability for defective products (85/374/EEC). No L 210/29.

[344] Recital 1 of the preamble of the EPLD.

[345] Article 1 of the EPLD.

production.[346] In order to balance the interest of producers and consumers and to reach a fair risk allocation, a bundle of rules is crystallised in the EPLD. Firstly, the scope of the producer not only includes the manufacturer of a finished product, but it also extends to the producer of raw materials, the producer of the components, the importer and any person or entity that purports to be the producer.[347] Secondly, "product" only refers to *movables*.[348] Thirdly, the strict product liability imposed on producers is not an absolute liability. A producer can free itself from bearing liability through specific defences.[349]

The EPLD is intended as a maximal harmonisation directive, meaning that any provision which is more protective than the directive is not allowed in Member States.[350] In addition, despite establishing a strict product liability, the EPLD respects the existing schemes under domestic contract (sales) laws or fault-based tort rules.[351] In this sense, if a product causes damage, then a consumer can still claim against the seller's liability on the basis of non-conformity. However, the freedom to apply these systems based on other grounds should not affect the application of the EPLD.[352]

6.2.3. Summary

The Member States generally transplanted strict product liability at the domestic level in two ways. Firstly, the majority of countries adopted a specific product liability statute.[353] Secondly, several

[346] The Recital 2 of the preamble of the EPLD states that "liability without fault on the part of the producer is the sole means of adequately solving the problem, peculiar to our age of increasing technicality, of a fair apportionment of the risks inherent in modern technological production."

[347] Article 3 of the EPLD.

[348] Article 2 of the EPLD.

[349] Article 7 of the EPLD. According to this article, a producer would not be liable in the circumstances that s/he did not put the product into the circulation, that the defect did not exist at the time of putting it into circulation, that the product was not manufactured for sale, that defect is due to the compliance of mandatory regulations and that he was unable to detect the defect at the time putting the product into circulation due to the state of scientific knowledge.

[350] Fairgrieve, Duncan et al. "Product Liability Directive" in Piotr Machnikowski (ed.) EUROPEAN PRODUCT LIABILITY: AN ANALYSIS OF THE STATE OF THE ART IN THE ERA OF NEW TECHNOLOGIES. Intersentia, 2016, 17-108, at 29-30.

[351] Article 13 of the EPLD.

[352] See Fairgrieve et al. (2016), supra note 350, at 36-38.

[353] Typical Member States are Belgium, Germany, Italy and Spain.

countries with a civil code tradition transplanted the rules into the tort chapter of their civil codes.[354] In order to ensure that Member States correctly enforce the EPLD and that new problems concerning the directive can be solved quickly, the directive should be reviewed every five years.

In the next section, we carry out a positive legal analysis to explore the extent to which strict product liability applies to 3D printing. Then, Chapter 7 uses economic criteria to answer the normative question: the extent to which strict product liability or the rule of negligence should be used to achieve the goal of deterrence and risk distribution with 3D printing.

6.3. The emerging new technologies and their impact on the application of the EPLD

As mentioned, when production is organised under the "separation model" in the context of 3D printing, a consumer has to firstly find a CAD file and then takes it to a fabricator who offers printing service. Therefore, the role of the "producer" is substantially taken over by two separate actors: the digital designer of the CAD file and the fabricator of the final product. To achieve the goal of deterrence, specific legal instruments should be offered to optimise the incentive of both parties.

Reports from the EU shows that the majority of Member States do not offer the injured party any type of extra-contractual protection from the damage caused by intangibles and services.[355] For the Member States who ensure tort liability to protect the injured parties from such damages, only two adopt strict liability.[356] In recent years, Member States are gradually adjusting their domestic law in response to the disruptive technologies which keep transforming the way of production. One outstanding reform takes place in the area of product liability law, as intangibles and the product obtained from services are increasingly explained as the "products" in the Member States. As a result, some of Member States which do not offer any form of extra-contractual protections are embracing strict product liability to protect injured parties who suffered damages from the defective intangibles and services.

[354] Typical Member States are France and the Netherlands.

[355] European Commission. (2018). Evaluation of Council Directive 85/374/EEC on the approximation of laws, regulations and administrative provisions of the Member States concerning liability for defective products: Final Report, at 69.

[356] In Greece and Lithuania, the damage caused by intangibles and services subject to strict liability. See id. at 70.

At the moment, Member States are attempting to extend the scope of strict product liability by redefining the following critical criteria: (1) the method of production; (2) the service/product dichotomy and (3) the tangible/intangible dichotomy. The following discussion will describe the extent to which Member States are different from each other in terms of interpreting these issues.

6.3.1. The controversy over the method of production

The first point that should be clarified is whether a product is defined in respect of the method of producing it. While the EPLD was promulgated in response to mass production, production activities conducted by non-professionals on a small scale were nonetheless widely observed in practice. Against this background, people may wonder whether "products" only refer to the ones that are industrially produced or whether the term includes all kinds of product irrespective of the production method.

Indeed, the EPLD explicitly states that "liability without fault should apply only to movables which have been *industrially produced*".[357] As a consequence, objects that are not industrially produced seem to be excluded. However, the answer to this question becomes blurred if additional sources of legal interpretation are referred. For instance, in the wording of Article 2 of the EPLD, no distinction in the means of production is made in defining the product. In addition, if we trace back to the original intent of the EPLD, which can be seen in the explanatory memorandum in 1976, we find that the notion of the product was explained irrespective of the methods of production.[358] Moreover, opinions in recent cases also do not support a distinction based on the method of production. For example, in *Henning Veedfald v. Arhus Amtskommune*, applying strict product liability to a product that is not industrially manufactured was confirmed by the European Court

[357] See Recital 3 of the preamble of the EPLD.

[358] The explanatory memorandum stated that the notion of the product should be *irrespective of the methods of production*. See Explanatory memorandum on the proposal for a council directive relating to the approximation of the laws, regulations and administrative provisions of the Member States concerning liability for defective products. Bulletin of the European Communities, Supplement 11/76, 14.

of Justice (ECJ).[359] Member States such as the Netherlands also have adopted a broad interpretation in their domestic laws.[360]

In Germany, according to the so-called "chicken-pest" case, whether a party is defined as the producer is partly determined by whether or not s/he runs a business. An individual would be defined as the "producer" if s/he ran a one-person business.[361] In other words, if an individual only takes part in production activities in an occasional way, s/he is not regarded as the producer. Therefore, the size of the business and its number of employees is not the key to delineating the scope of the "producer" according to the directive. Instead, it is the nature of the business that determines whether or not a party is considered to be the producer. In the EPLD, a party can escape strict product liability if s/he can prove that the product is not manufactured for sale or other economic purposes.[362]

To conclude, the way to manufacture a product has been broadly interpreted in practice. The goods that are not produced on an industrial scale thereby may also fall into the scope of the "product" in the EPLD. It implies that strict product liability is not limited to mass producers. Instead, a small business that offers products for commercial purpose can also be subject to strict product liability.

6.3.2. The controversy over the product/service dichotomy

The second controversial issue relates to the dichotomy between product and service. At the moment, Member States have not reached a consensus on whether the service provider is subject to extra-contractual resolutions, when a product is provided from his/her service. The majority of Member States do not adopt any form of extra-contractual liability toward a service provider.[363]

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[359] See Case C-203/99, Veedfald v Arhus Amtskommune [2001] ECR I-3569.

[360] Keirse, Anne Lucienne Maria. "Product Liability in the Netherlands" in Piotr Machnikowski (ed.) EUROPEAN PRODUCT LIABILITY: AN ANALYSIS OF THE STATE OF THE ART IN THE ERA OF NEW TECHNOLOGIES. Intersentia, 2016, 311-358, at 317.

[361] See *Entscheidungen des Bundesgerichtshofes in Zivilsachen* (BGHZ) 52, 91.

[362] Article 7(c) of the EPLD.

[363] These countries are Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Finland, Hungary, Italy, Latvia, Luxembourg, Poland, Portugal, Romania, Spain, Sweden and the UK. See supra note 355, at 69.

In some other jurisdictions, the liability for services could be considered on a fault-basis.[364] In practice, as personal injury and material damage are sometimes caused by a product obtained in a service context, controversies arise whether such service providers are more like traditional service providers or producers.[365]

Whether the service provider, who aims at offering a product through service, is subject to strict liability becomes a topical issue. As the EPLD does not clarify this issue, it is each Member State that has the discretion to decide what kind of liability applies to such service providers. In case law, Advocate General Colomer argued in *Henning Veedfald v. Arhus Amtskommune* that the EPLD was not intended to apply to services, as a result of which service providers would not be subject to strict product liability arising from defects in their services or defective goods used in their services.[366] However, the ECJ rejected this interpretation, expressing a view that "it is sufficient to observe that the case involved the defectiveness of a product – used in the course of providing a service – and not any defect in the service as such."[367] In other words, while the service *per se* (i.e., the kidney transplant operation) was not defective, the fact that the product (i.e., the fluid prepared to flush the kidney) offered in the service was defective could result in applying strict liability to the service provider.

To date, many countries tend to apply strict product liability toward service providers by clarifying that the final objects offered by their services are deemed as a form of "product". For example, In Denmark, service is conventionally excluded from the application of Danish Product Liability Act. However, if the service aims at providing material goods, it would be deemed more like a product

[364] Besides Italy and the Netherlands, other countries that adopt this approach are Estonia, France, Malta, Slovakia and Slovenia. See supra note 355, at 69.

[365] Hojnik, Janja. "Technology neutral EU law: digital goods within the traditional goods/services distinction." International Journal of Law and Information Technology 25, no. 1 (2017): 63-84.

[366] See Case C-203/99, Veedfald v Arhus Amtskommune [2001] ECR I-3569, recitals 15-17.

[367] See Case C-203/99, Veedfald v Arhus Amtskommune [2001] ECR I-3569, recital 12.

rather than service.[368] As a result, strict product liability would apply to this scenario in Denmark. A similar interpretation can also be found in Finland and Luxembourg.[369]

The issue could be even more complicated when it comes to the circumstance where the production is based on an individual order. In this case, whether the service provider is subject to strict product liability or not depends on the degree to which the consumer is involved. If the consumer "has decided on the design of the object", then this scenario is more likely to be decided as a service rather than a production process. As a result, a party who offers customised products may still be deemed as a conventional service provider and thereby subject to contractual or fault-based liabilities.[370]

6.3.3 The controversy over the tangible/intangible dichotomy

According to the EPLD, "products" are defined as *movables*.[371] In this regard, any intangible goods are excluded from the directive. This interpretation was reasonable with traditional mass production since the products that are placed into circulation are mostly in movable nature. However, as intangibles are playing an increasingly important role in finalising the product, in recent years damages are found to be substantially linked with intangible goods.

Traditionally, the tangibility/intangibility dichotomy was often used to decide the issue of whether or not an intangible good was a product.[372] An intangible good could be regarded as a product only if it is materialised on a tangible medium.[373] In this regard, intangibles like book contents and pure

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[368] Holle, Marie-Louise and Peter Møgelvang-Hansen. "Product Liability in Denmark", in Piotr Machnikowski, EUROPEAN PRODUCT LIABILITY : AN ANALYSIS OF THE STATE OF THE ART IN THE ERA OF NEW TECHNOLOGIES, Intersentia, 2016, 155-172. at 160.

[369] See European Commission (2018), supra note 355, at 70.

[370] See Keirse (2016), supra note 360, at 318.

[371] "For the purpose of this Directive 'product' means all movables, with the exception of primary agricultural products and game, even though incorporated into another movable or into an immovable." See Article 2 of the EPLD.

[372] Reutiman, Joseph L. "Defective Information: Should Information Be a Product Subject to Products Liability Claims." Cornell JL & Pub. Pol'y 22 (2012): 181.

[373] This proposition can also be found in jurisdictions outside Europe. For example, in the US, Section 19 of the Restatement (Third) of Torts also defines the product as tangible property. Therefore, purely electronic data and codes, as well as non-embedded software, are not included. See Beck and Jacobson (2017), supra note 1.

electronic data are not defined as products.[374] Similarly, professionals like doctors who give prescriptions to patients, and consultants who offer advice are thereby excluded from product liability. The information provided in this way is considered to take the function of keeping its receivers well informed. Rather, it results in no substantive function on the final product.

This tangibility/intangibility dichotomy was widely respected in the Member States for a long time. Other than Greece and Lithuania, most countries in the EU do not admit intangible goods as products, unless they can be embedded in a material medium. Therefore, whenever a non-embedded good causes damage, according to the domestic law of most jurisdictions, the party that developed the goods is not subject to strict liability. Conventionally, most jurisdictions only guarantee the victim a contract-based redress.[375] In comparison, while intangible goods are not regarded as "products" in some other Member States, these states grant victims a right to claim for losses against the developer of the non-embedded goods through the rule of negligence.[376] In addition, since non-embedded goods are not distinguished from the embedded ones in domestic law, developers of the non-embedded goods can be strictly liable in Greece and Lithuania.

When *computer programs* were first linked with damages, they were not regarded as the product. Only the material medium that operated or carried the computer program was interpreted as the "product".[377] In recent years, however, intangibles, especially non-embedded software and even intelligent systems, have been perceived as the main drivers of production.[378] Against this

[374] Howells, Geraint, Christian Twigg-Flesner, and Chris Willett. "Product Liability and Digital Products." In Tatiani-Eleni Synodinou, Philippe Jougleux and Thalia Prastitou (eds.) EU INTERNET LAW, Springer, Cham, 2017, 183-195. The defective information delivered to a material device (e.g. a GPS device) is separable to the device so that it is not qualified as a "tangible" product. See Reutiman (2012), supra note 372, at 195.

[375] These countries are Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Finland, Hungary, Italy, Latvia, Luxembourg, Poland, Portugal, Romania, Spain, Sweden and the UK.

[376] See European Commission (2018), supra note 355, at 71.

[377] See Written Question No 706/88 by Mr Gijs de Vries to the Commission: Product Liability for Computer Programs [1989] OJ C114/42. This explanation also had an impact on domestic legal practice. For example, intangible goods like information or software without a material carrier are not defined as the "product" under Dutch law. Software is considered as a product only if it is embedded in a movable carrier. See Keirse (2016), supra note 360, at 318.

[378] The products in this era are increasingly under the control of computer software or even intelligent systems. In this sense, the errors generated by running software or using intelligent robotics may cause severe harms. See Gurney, Jeffrey K. "Sue my car not me: Products liability and accidents involving autonomous vehicles." U. Ill. JL Tech. & Pol'y (2013): 247; Vladeck, David C. "Machines without principals: liability rules and artificial intelligence." Wash. L. Rev. 89 (2014): 117; Calo, Ryan. "Robotics and the Lessons of Cyberlaw." California Law Review (2015): 513-

background, one of the principal transformations is that intangibles are no longer merely perceived as channels for delivering information. Instead, they play a substantial role in determining the function and performance of the final product.[379] For example, the question that is immediately asked is whether the non-embedded software should fall into the scope of the "product" under the EPLD.[380] As indicated in the product/service discussion, where the directive does not preclude the Member States from categorising service as the product, the directive also permits the Member States to further define non-embedded software as the product in their domestic laws. Recently, some countries have gradually expanded strict liability to include non-embedded software in practice.[381] For example, computer software is explicitly defined as a movable in the Law of Obligations Act in Estonia.[382] Likewise, courts in Germany also imply that online software, which is not embedded in the material medium, is the "product" under the German Product Liability Act.[383]

563; Choi, Bryan H. "Crashworthy code." Wash. L. Rev. 94 (2019): 39; Abbott, Ryan. "The reasonable computer: Disrupting the paradigm of tort liability." Geo. Wash. L. Rev. 86 (2018): 1.

[379] Alheit, K. "The applicability of the EU Product Liability Directive to software." Comparative and International Law Journal of Southern Africa 34, no. 2 (2001): 188-209. As professor Hubbard articulated, machines are become more sophisticated because of the increasing autonomy and intelligence. He further mentioned that "Many of these machines will be sufficiently large and mobile enough to cause physical injury and death," See Hubbard, F. Patrick. "Sophisticated robots: Balancing liability, regulation, and innovation." Fla. L. Rev. 66 (2014): 1803, at 1806.

[380] The European Commission asks a specific question in the recent evaluation of the EPLD: "whether apps and non-embedded software or the Internet of Things (IoT) based products are considered as products under the directive". See COMMISSION STAFF WORKING DOCUMENT Evaluation of Council Directive 85/374/EEC of 25 July 1985 on the approximation of the laws, regulations and administrative provisions of the Member States concerning liability for defective products Accompanying the document Report from the Commission to the European Parliament, the Council and the European Economic and Social Committee on the Application of the Council Directive on the approximation of the laws, regulations, and administrative provisions of the Member States concerning liability for defective products (85/374/EEC), SWD/2018/157 final.

[381] A similar trend is also observed on the other side of the Atlantic. According to the Reporters of the Product Liability Restatement, when a court decides whether strict liability applies to software, it "draw[s] an analogy between the treatment of software under the Uniform Commercial Code and under products liability law". In the US Uniform Commercial Code, "software that is mass-marketed is considered a good." See RESTATEMENT (THIRD) OF TORTS: PROD. LIAB. § 19 cmt. d (1998).

[382] In § 1063 (under Division 3 "Liability for Defective Product" of the Chapter 53 "Unlawful causing of damage"), it states that "Any movable is deemed to be a product, even if the movable constitutes a part of another movable or if the movable has become a part of an immovable, and electricity and computer software are also deemed to be movables."

[383] See Magus, Ulrich. (2016). "Product liability in Germany", in Piotr Machnikowski (ed.) European Product Liability: An Analysis of the State of the Art in the Era of New Technologies. Intersentia, 237-274, at 245. In actual, there are also cases with opposite opinions. See Erman/Schiemann §2 ProdHaftG.

According to Professor Howells, if a digital good only takes the role of delivering information, then the EPLD does not apply to this subject matter. However, the directive should apply to digital goods (either embedded or non-embedded) whenever they cause harms.[384] In this regard, instead of the tangibility/intangibility dichotomy, the *function* taken by digital goods seems to be a preferable benchmark to decide the standard of liability.[385]

6.3.4. Summary

According to the original intent of the EPLD, only the actor who industrially produces movables are subject to strict liability. In contrast, service providers who engage in offering products, makers of digital contents and actors who run a small business are excluded from bearing strict liability. As the pattern of production is substantially transformed with the adoption of new technologies, the potential of production greatly outweighs our imagination. The fact that service providers account for a large number of productions, that digital contents can substantially influence the function of a material product and that non-professional individuals intensively engage in production activities indicates that the product liability regime which was designed for mass production cannot catch up with the pace of production. Against this background, there is a necessity to redefine the scope of strict product liability in the new era. The analysis in this chapter has shown that this redefinition has already taken place at the domestic level. Not surprisingly, divergence and controversy are observed in this course.

Some of the most important transformations within the product liability regime could be summarised. Firstly, strict product liability is not limited to mass producers. Entities or individuals who run a small business may also be subject to strict liability. Secondly, service providers who specialise in offering product in their service are increasingly subject to strict product liability

[384] See Howells et al. (2017), supra note 374. Besides Howells, scholars from different Member States are also in line with the proposition that product should be interpreted broadly at least to the scope of intangible objects. For example, although no doctrine so far can be found regarding this issue in Spain, Spanish Scholars believe that intangible goods like misinformation that is circulated through the Internet should be considered products. See Martín Casals, Miquel, and Josep Solé Feliu. "Product liability in Spain." In Piotr Machnikowski (ed.) EUROPEAN PRODUCT LIABILITY: AN ANALYSIS OF THE STATE OF THE ART IN THE ERA OF NEW TECHNOLOGIES. Intersentia. 2017, 407-459, at 418.

[385] For example, Fairgrieve et al. hold the opinion that "defective information as such could give rise to liability of the producer of that information would be in line with an effective application of the Product Liability Directive." See Fairgrieve et al. (2016), supra note 349, at 50.

nowadays. One exception regarding this point is that a service provider might not bear strict product liability, if the product s/he offered is highly customised. Thirdly, digital content and software that are not embedded into a material medium are also increasingly regarded as the "product" at the domestic level.

Having analysed the recent development within the product liability regime in Europe, the discussion in the next chapter is to examine how the transformation implies to the liability borne by relevant parties in the contest of 3D printing.

6.4. Product liability in the context of 3D printing: lessons from the positive legal analysis

As analysed, while 3D printing can be distinguished into various business models, not all of them result in sharp disruptions compared with traditional manufacturing.[386] In the one-stop model, strict product liability seems to be still justified in this case. The reasons are twofold. Firstly, the complete process of production is still accomplished within a single entity, which is largely hidden from the consumer side. Secondly, the entity is normally an undertaking, who is more capable of bearing the risk.

In addition, the liability for specific actors in the supply chain would not change despite the application of 3D printing. For example, *raw material providers* and *3D printer manufacturers* are indispensable. Consistent with the traditional paradigm, they are liable only if the raw materials or 3D printers provided by them are defective *per se* and the damage is caused by the defective raw materials and 3D printers. As a result, in the context of 3D printing, raw material producers, component producers as well as 3D printer producers will not bear liability as long as they can prove that their 'products' (i.e. raw materials, components and 3D printer) work well.

Controversies over the liability of actors under separation models arise when digital designing and physical fabrication are accomplished by different parties.[387] Unlike traditional mass production

[386] See the discussion in Section 3.2.1.

[387] For example, scholars reached quite different conclusions on the issue of whether CAD file designers should be strictly liable for the harm caused by the final product. While some scholars hesitate to apply strict liability to digital designers (e.g. Engstrom 2013), some others are inclined to pose strict liability. See Lindenfeld (2016), supra note 1, at 79. Also see European Commission, *Evaluation of Council Directive 85/374/EEC of 25 July 1985 on the approximation of the laws, regulations and administrative provisions of the Member States concerning liability for defective products*, SWD(2018) 157 final, p. 53ff.

where the manufacturer takes control of the whole production process, 3D printing that adopts the "separation model" disrupts production in a way that key production activities are fulfilled by the digital designer and fabricator who are strangers each other. Therefore, it is crucial to understand what kind of liability these parties are subject to and whether this arrangement is efficient. The analysis in Section 6.4 explores the extent to which different *CAD file makers*, as well as *fabricators* under various business models, are subject to product liabilities. Chapter 8 and Chapter 9, respectively from the perspective of deterrence and risk-bearing, will pay closer attention to assess whether the implications from Section 6.4. results in an efficient outcome.

6.4.1. Product liability for CAD file makers: a positive legal analysis

CAD file makers pose risks in the process of digital modelling. The question to be answered in this subsection is: from a positive legal perspective, what kind of liability is the CAD file maker subject to in different business models?

One problem that needs to be contemplated in all the models under Model A is whether a CAD file is defined as a "product". The discussion on this issue rests on the previous analysis of whether or not non-embedded software is a product. According to previous positive legal studies, the majority of Member States have not accepted the non-embedded software as a product while, on the other hand, courts are inclined to interpret non-embedded software as a product.[388] It can thus be expected that while a CAD file, which performs in the same way as other non-embedded software, can result in direct material effect and lead to harm to some extent, a person who makes a CAD file and subsequently sells it online can be subject to different liability rules in different jurisdictions. For instance, a CAD file maker will be subject to contractual liability in Italy, negligence rules in the Netherlands, and strict product liability in Estonia. More complicated, in countries like Germany, due to disparities observed in cases, a CAD file maker may not be able to determine readily whether negligence or strict liability will be imposed.[389]

In addition to the common dispute on the nature of the CAD file, the standard of liability could be different when specific conditions are taken into account under various business models.

[388] See Section 6.3.3, such an inclination can be seen in Germany and Estonia.

[389] See the discussion in Section 6.3.3.

Product liability under Model A.1

Model A.1 refers to the scenario in which a person gains the CAD file from an open-source platform. As parties relying on this business model to offer CAD files are not for the monetary purpose, strict product liability would not apply to them.

According to the previous positive legal analysis, eighteen Member States do not have any form of extra-contractual liability for the damage caused by intangibles. In the context of Model A.1, the situation in these countries would be even worse, since no contractual liability exists between the CAD file maker and the victim in this open-source environment.[390] As a consequence, the product risk generated by CAD file makers under Model A.1 cannot be deterred by either contractual or extra-contractual liabilities in these jurisdictions.

In comparison, in the Member States where fault-based liabilities can be applied to intangibles, CAD file makers might be subject to liability provided that victims can prove the damage is caused by the *fault* of the CAD file makers.

To conclude, according to the positive legal analysis, CAD file makers under Model A.1 are only subject to fault-based tort liabilities in a few jurisdictions in Europe, while no protection is offered to victims in the majority of Member States.

Product liability under Model A.2

Model A.2 represents the case where a person purchases the CAD file from an online marketplace. According to the previous positive analysis, conventionally the majority of countries in the EU does not offer any extra-contractual liability to intangibles, so that CAD file makers who run a business under Model A.2 are subject to contractual liabilities. This situation, however, is gradually changed since some countries gradually interpret in their domestic laws or cases that the intangibles which are not fixed on material mediums fall into the scope of “products”.

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[390] Twigg-Flesner, Christian. “Conformity of 3D prints–Can current Sales Law cope?” In R. Schulze and D. Staudenmeyer, DIGITAL REVOLUTION–CHALLENGES FOR CONTRACT LAW, Nomos/Hart, 2015, 35-65.

The implication from the positive legal analysis has a great impact on the liability borne by the CAD file designers under Model A.2. On the one hand, these parties are still subject to contractual liability in most countries. In this regard, the implications of contractual liabilities offered by Part II hold in this scenario, and tort liability offers no extra incentive to CAD file designers under Model A.2 beyond contractual liability. On the other hand, CAD file designers who run a business under Model A.2 have to bear in mind that the damages caused by their defective CAD files could incur strict liability in particular Member States.

Product liability under Model A.3

Under Model A.3, a person obtains the CAD file in cooperation with the CAD file maker. Therefore, the CAD file obtained from Model A.3 is not only an intangible that is not fixed on a material medium, but also a "product" gained from service.

Conventionally, based on the service/product dichotomy and the tangible/intangible dichotomy, taking the findings of the previous positive legal analysis into account, the CAD file makers under this Model A.3 are aware that they would be subject to contractual liability in the majority of Member States for damages caused their defective products. In other jurisdictions, they are subject to fault-based rules. Only in Greece and Lithuania, where intangibles are also regarded as the "products", they are at the risk of being strictly liable.

However, the recent development of product liability regime may undermine the expectation of CAD file makers to some extent, as Member States such as Estonia and Germany are inclined to interpret non-embedded intangibles as "products". What is more, in countries like Denmark and Finland, actors who are responsible for offering a "product" in the service providers are likely to be strictly liable. However, it is not clear whether a party is subject to strict product liability when the damage is caused by the non-embedded intangible offered by him/her from a service context. Therefore, there is a higher degree of uncertainty when it comes to the form of liability that a CAD file maker has to bear in under Model A.3.

6.4.2. Product liability for fabricators: a positive legal analysis

Apart from the risks that are generated in the digital design process, risks are also generated in the process of fabricating the CAD file into the final physical object.

Unlike traditional mass production, in which manufacturers dominate the process of production, fabricators that run a business under separation models rely on the CAD file offered by the consumer. Therefore, fabricators under Model B are actually taking the role of service providers. According to the positive legal analysis previously in this chapter, despite extra-contractual liability being applicable in several countries, conventionally service providers are only subject to contractual liability in the majority of Member States.[391] If this system is wholly retained without change in the context of 3D printing, fabricators can reasonably estimate that they are unlikely to be strictly liable, unless they engage in fabrication in specific countries (i.e. Greece and Lithuania). In other words, their incentive to behave appropriately would be largely constraint by the contract concluded between the consumer and them. However, as analysed, some Member States now are extending the scope of product liability to the scenario where a product is offered from a service context.[392] In this sense, 3D printing fabricators are expected to bear a higher liability risk. They will be thus provided with an extra incentive to behave appropriately.

6.4.3. Summary

In brief, there is a large divergence at the domestic level on the form of the liability for CAD file makers and fabricators. As analysed, this divergence could be even considerable differentiated by the business models that these actors rest on. Considering the recent reforms of product liability regime across Europe, the potential liability borne by CAD file makers and fabricators in specific business models can be summarised in Table 8.

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[391] See the discussion in Section 6.3.2.

[392] Such as Finland and Denmark, for more details, see the discussion in Section 6.3.2.

Table 8: The liabilities of relevant parties in the context of 3D printing

Business Model	Who might be liable?	Activity features	The form of liability according to positive legal analysis	Recent changes
Model A.1	CAD file makers	Non-business, offering intangibles,	In 18 Member States: no liability In 9 Member States: negligence is also applicable	-
Model A.2	CAD file makers	Offering intangibles	In 18 Member States: contractual liability only In 7 Member States: negligence is applicable In 2 Member States: strict liability is applicable	Strict product liability extended to intangibles (e.g. Estonia and Germany)
Model A.3	CAD file makers	Offering intangibles, service		Not clear
Model B	Fabricators	Service		Strict product liability extended to service providers (e.g. Denmark, Finland, etc.)

According to the table, two important conclusions can be drawn.

Firstly, so far most Member States have not any form of extra-contractual liability for the damage caused by intangibles or the damage caused by a product generated in a service context. This implies that the risk from the emerging 3D printing technologies under various business models can only be addressed through the contract concluded between the relevant parties (i.e., the CAD file maker and the fabricator) and consumers. In this scenario, the findings on contracting for product risk in the context of 3D printing that were concluded in Part II persist.

Secondly, in recent years, an expansion of product liability has been embraced at the domestic level. Intangibles, as well as products that are obtained as part of a service, have been especially targeted by judges. Under this background, besides Greece and Lithuania where strict liability has already applied to service providers and intangibles, many countries enlarge the scope of product liability by blurring the product/service dichotomy or tangible/intangible dichotomy. As a result, CAD file makers who run a business under Model A.2 and fabricators who offer the printing service are likely subject to strict liability.

6.5. Chapter conclusion

To conclude, the main purpose of this chapter is analysing the extent to which actors running a business with 3D printing are subject to tort liabilities. For 3D printer manufacturers, raw material providers and components providers, their liability is not significantly different from the traditional context. In this regard, Member States adopt similar attitudes that they will be strictly liable only if the damage is caused by the defect in their "products" (i.e. 3D printer, raw material and component).

The main controversy is to which kind of liability CAD file makers and fabricators are subject. Traditionally, damages caused by intangibles and service fall into the scope of contractual liability in the majority of Member States. A few countries adopt fault-based rules and only two apply strict liability. The main reason behind this landscape is that intangibles and services are deemed less likely to cause material damages. If this system is completely maintained without any change in the context of 3D printing, then it could be imagined that CAD file makers under Model A and fabricators under Model B are mainly subject to contractual liability. In this regard, tort liability plays a limited role in dealing with product risk in the context of 3D printing

However, as (1) products are increasingly offered by the non-industrial way of production, (2) intangibles are playing an increasingly important role in determining the function of the final product and (3) more products are offered by service providers rather than mass producers, some European countries choose to extend the application of product liability regime by interpreting intangibles and products offered through service as the "products". This shift has a great impact on the liability borne by CAD file makers and fabricators under various business models. In general, CAD file makers and fabricators seem to be at a higher risk of bearing strict product liability.

According to the positive legal analysis, Member States have not reached a consensus on the form of liability of CAD file makers and fabricators. On the one hand, the fact that some countries tend to extend the scope of product liability indicates that tort liability is expected to play a role where contractual liability fails. On the other hand, the fact that not all countries follow this expansion and many of them are hesitant to apply extra-contractual liabilities implies that tort liability may not be an appropriate approach to deal with the product risk generated by intangibles and services. Having said that, there is a pressing need to discuss the performance of tort liability in the context of 3D printing. In the next two chapters, how different liability rules influences social welfare in the context of 3D printing will be discussed. Such an analysis focuses on the extent to which different liability rules are present to influence the incentive of CAD file makers and fabricators under various business models. What is more, risk-bearing as an aspect of influencing social welfare will also be considered in the assessment of various liability rules.

Chapter 7. Product Liability at the Crossroads of 3D Printing: A (Normative) Law and Economics Perspective

The analysis in Part II has discussed the extent to which CAD file makers and fabricators are subject to extra-contractual liabilities in different Member States, which also presents an enormous divergence among Member States. From this chapter, the analysis attempts to evaluate the current legal framework by explaining the efficiency of liability rules under various business models in the context of 3D printing. A preferable liability conditioned by particular business model should be the one that results in the most effective outcome.

In practice, the economic theory has played a significant role in entrenching the current product liability regime. Factors such as the importance of activity level, the asymmetric information between the parties, the errors made by the court and the capacity of producers to spread the losses explain why strict liability is superior to fault-based rules in the production section.[393] Judges in case laws also explicitly stressed the importance of strict liability in optimising the incentive of stakeholders and shifting the risk.[394] Under this background, the main interest of Chapter 7 and Chapter 8 is to examine whether these justifications still hold in the context of 3D printing. This chapter delves into the issue of deterrence effect, and the next chapter shifts to the perspective of risk-spreading.

[393] See Polinsky and Rogerson (1983), supra note 231; see also Landes and Posner (1985), supra note 239; Daughety and Reinganum (2006), supra note 255; Ordover, Janusz A. "Products Liability in Markets with Heterogeneous Consumers." The Journal of Legal Studies 8, no. 3 (1979): 505-525; Wickelgren, Abraham L. "The inefficiency of contractually-based liability with rational consumers." Journal of Law, Economics, and Organization 22, no. 1 (2006): 168-183; Goldberg, John CP, and Benjamin C. Zipursky. "The easy case for products liability law: A response to professors polinsky and shavell." Harvard Law Review 123, no. 8 (2010): 1919-1948.

[394] See, for example, Escola, supra note 315, at 440-441

From the perspective of deterrence, a preliminary insight is that, if the original justifications are not considerably dismantled, strict liability might be superior to fault-based rules with respect to optimising the incentive of the CAD file makers and fabricators, as a result of which the expansion of strict liability in practice should be encouraged; if, however, these justifications are non-existent in the context of 3D printing, which means that strict liability presents little improvement on deterrence, the expansion of strict liability in practice is unreasonable.

This chapter proceeds as follows. It firstly focuses on the issue of activity level. By doing so, this chapter explores the issue of which liability rule can induce relevant parties to take the optimal level of activity. In the second section, the discussion shifts to the perspective of information disclosure. If a liability rule can play a role in disclosing the full cost of a product, then this liability rule is assumed to induce consumers to make a better decision by comparing costs and utilities. Thirdly, various errors made by the courts are taken into account. If a liability rule is less sensitive to errors and the errors result in less impact on the behaviour of relevant parties, this liability rule could be superior. In each section, a theoretical analysis is followed by a specific application to the context of 3D printing, the purpose of which is to compare the efficiency of different liability rules in this scenario. The last section concludes the findings on the superiority of liability rules from the perspective of deterrence; policy recommendations are also given.

7.1. Product liability from the perspective of activity level

Providing relevant parties with the incentive to optimising their behaviours serves as the primary goal when dealing with the accident caused by production.[395] As for the accidents caused by product risk, the level of social welfare is influenced by the behaviour of relevant parties in terms not only of precautions but also of the level of activity.[396] The previous discussion showed that in a setting where parties are able to bargain sufficiently with each other and none of them suffers information problems, parties could correctly include the optimal care level and activity level in

[395] See Calabresi, Guido. THE COST OF ACCIDENTS: A LEGAL AND ECONOMIC ANALYSIS. Yale University Press. 1970.

[396] See Posner, Richard A. "A theory of negligence." The Journal of Legal Studies 1, no. 1 (1972): 29-96; Posner, Richard A. ECONOMIC ANALYSIS OF LAW. 1973. Little, Brown, Boston. See also Brown, John Prather. "Toward an economic theory of liability." The Journal of Legal Studies 2, no. 2 (1973): 323-349.

the contract. As a result, the optimal incentive would be provided to contractual parties without legal intervention.

However, the previous discussion in Chapter 5 also showed that optimal deterrence is unlikely to be achieved through a contractual relationship due to the cost of bargaining and the existence of information asymmetry. Even in the scenarios where contractual parties are able to bargain with each other sufficiently and exchange information in a frictionless manner (e.g. Model A.3, Model B.1 and Model B.3), contract may fail to result in the optimal deterrence effect, since it would be challenging for one contractual party to accurately assess and conclude the optimal activity level of the other party into the contract.[397] Therefore, in the scenarios where bargaining is smooth, parties are incentivised to behave appropriately to the extent that is*observable* to both parties.

Apart from contracting over liability, tort liability also serves as a way of providing incentives to parties. In this sense, provided that parties cannot negotiate to maximise their joint benefit, liability rules may come into deciding the allocation of risk in a way that the maximisation of social welfare is achieved.[398] Being subject to liability rules, parties that generate product risk would be incentivised to take precautions and control their activities by comparing the utility and cost of a precaution and an incremental activity. The core issue in this subsection is exploring which kind of liability rule could provide relevant parties with the incentive to optimise their behaviours.

7.1.1. Activity level under various liability rules

To achieve the optimal deterrence effect, a liability rule should not only incentivise relevant parties to pick up the optimal level of precaution, which is met at the last point that an additional investment of precaution would reduce more accident cost, but also induce these parties to optimise their activities, which is unobservable by outsiders. Therefore, one kind of liability rule is better than the other given that it could incentivise all the relevant parties to take optimal level of care as well as optimal level of activity.

[397] See the discussion in Section 5.1.3, Section 5.2.1 and Section 5.2.3.

[398] See Priest (2020), supra note 201.

As modelled previously, the scale of social welfare is determined by four variables: the care level of the producer (denoted as "x"), the care level of the user ("y"), the activity level of the producer ("w") and the activity level of the user ("z").[399] Furthermore, a consumer makes a decision by comparing the utility ("U_C") that s/he gains from the product and the cost of obtaining the product. Therefore, the amount of social welfare could be determined as follows:

$$U_C(q) - q(c + wx + zy + pwz(x,y)D)$$

In a unilateral case, product risk is only related to either the behaviour of the injurer or the behaviour of the victim. In the event that only the injurer can influence the accident cost, the socially optimal outcome could be achieved by imposing strict liability on the injurer, because the injurer understands that s/he is the party to bear all the costs so that the optimal level of care and the optimal level of activity have to be taken by him to minimise the cost.[400] In another event that only the injured party can influence the accident cost, the socially optimal outcome could be achieved by imposing no liability on the injurer, because the victim will be induced to optimise his/her level of care as well as the level of activity. Therefore, in the unilateral case, there is a kind of "*most suitable party*" to be targeted by law.

The situation is complicated when it comes to a bilateral accident, in which the behaviour of both parties has an impact on social costs. To achieve the socially optimal outcome, not only the care level and the activity level of the *injurer* but also the care level and the activity level of the *victim* need to be optimised. In other words, reflected in economic models, we wonder whether the four variables (i.e., x, y, w and z) can be optimised concurrently within one liability rule. The literature on tort law and economics has shown the deterrence effect of various liability rules in-depth. It has been proved that none of the liability rules found in theory can optimise all four of the variables at the same time.[401] As the first-best solution does not exist, a second-best solution should be decided to reduce accidents caused by product risk. In theory, a variety of choices serve as the candidates

[399] See the discussion in Section 4.1.2.

[400] Posner, Richard A. "Strict liability: a comment." The Journal of Legal Studies 2, no. 1 (1973): 205-221.

[401] See Shavell (1980), supra note 217; Shavell (2009), supra note 212, at 29-30.

for the second-best solution. For example, the rule of negligence has been shown to optimise the behaviour of the victim (i.e., y* and z*) and to incentivise the injurer to take an optimal care level (i.e., x*); however, the injurer would undertake excessive activities in these circumstances.[402] In comparison, if we add a defence of negligence to strict liability, which means that the consumer's fault can lead the injurer to escape the liability (i.e., the defence of contributory negligence) or reduce its liability (i.e., the defence of comparative negligence), it turns out that the injurer will be incentivised to optimise its behaviour (i.e., x* and w*) and the victim will be induced to take an optimal care level (y*).[403] However, in this latter case, the activity of the victim will be excessive. In the bilateral accident, the extent to which one liability rule is more effective than another can only be answered in a concrete scenario. As we discover, while both the rule of negligence and strict-liability-based rule can induce every party to take an optimal care level, their effects on activity level are totally different.

The essence that different liability rules result in activity levels differently stems from the answer to the question of which party would *ultimately* internalise the cost given all parties having taken the optimal level of care. The party who ultimately internalizes the costs when both parties take optimal care is also called the "residual risk bearer".[404] Therefore, determining which party to optimise activity level is de facto the process to evaluate which should be the residual risk bearer. If a party is chosen as the residual risk bearer, provided that due care level is set up optimally, not only s/he will take this optimal care level, but in the areas where courts/regulators fail to observe the risk s/he would be also be motivated to optimise the behaviour.

Therefore, the dilemma when tort liability is used to deal with a bilateral accident is that it cannot promise a socially optimal outcome. In practice, a second-best choice is achieved by choosing the "most suitable party" to bear the residual risk. According to the literature, if the activity of the

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[402] See Posner (1972), supra note 396; Brown (1973), supra note 396; Diamond, Peter A. "Single activity accidents." The Journal of Legal Studies 3, no. 1 (1974): 107-164; Diamond, Peter A. "Accident law and resource allocation." Bell Journal of Economics 5, no. 2 (1974): 366-405.

[403] See Brown (1973), supra note 402.

[404] For the discussion on the residual risk bearer, see Shavell (1980), supra note 217. Recent studies on this issue can be seen in Carbonara, E., Guerra, A., & Parisi, F. (2016). Sharing Residual Liability: The Cheapest Cost Avoider Revisited. The Journal of Legal Studies, 45(1), 173-201. The determination of the residual risk bearer is not only crucial in terms of deterrence, but as we will discuss later in Part III, it is also of great importance to risk-shifting. The residual risk bearer, given risk-averse, has the motive to shift his/her risk. See Dari-Mattiacci, G., and Francesco Parisi. "The economics of tort law: a précis." In Jürgen Backhaus (ed.), THE ELGAR COMPANION TO LAW AND ECONOMICS (2nd ed.) 2005, at 87-102. Cheltenham: Edward Elgar.

injurer is expected to generate much higher risks than the activity of the victim, then the strict-liability-based rule is preferable. On the other hand, if controlling the activity of the victim is more important, the rule of negligence is desirable. In practice, if it is obvious that one party generates more risk than the other, the "most suitable party" could be easily determined. In contrast, the "most suitable party" might not be easily identified, given that both parties can take some measures to reduce the accident.

There is another voice in traditional theory that only the party who performs an ultra-hazardous activity is linked with strict liability.[405] This trend, however, is recently criticised by Professor Shavell. He contends in a paper that if the activity *itself* is dangerous, then no matter whether it is a common activity (such as production or driving) or uncommon, strict liability is applicable.[406] This explanation is consistent with the goal of efficiency. If the party with more risky activities, rather than the one with fewer risk activities, is chosen as the "most suitable party", given all other factors equal, providing this party with an incentive to behave appropriately seems to generate more social welfare.

The discussion above also serves as the ground for applying strict liability on producers.[407] In the following two subsections, the discussion firstly explains how activity level serving as a determinant influences the allocation of product risk in the traditional context and, more importantly, the extent to which this paradigm applies to the context of 3D printing is examined.

7.1.2. Activity level in the context of traditional mass production

A variety of parties are involved in the supply chain under traditional mass production, and the most important two are upstream producers and downstream suppliers. This subsection offers an exposition on the difference of their liability from the perspective of activity level.

[405] Priest, George L. "Strict products liability: the original intent." Cardozo L. Rev. 10 (1988): 2301; Henderson Jr, James A. "Echoes of Enterprise Liability in Product Design and Marketing Litigation." Cornell L. Rev. 87 (2001): 958; Simons, Kenneth W. "The Restatement (Third) of Torts and Traditional Strict Liability: Robust Rationales, Slender Doctrines." Wake Forest L. Rev. 44 (2009): 1355.

[406] Shavell, Steven. "The Mistaken Restriction of Strict Liability to Uncommon Activities." Journal of Legal Analysis 10 (2018).

[407] See Landes and Posner (1985), supra note 239, at 549-550; see also Shavell (2009), supra note 401, at 31-32.

As observed in the positive legal analysis, a shift from the negligence rule to strict liability regarding producers took place in the 1960s. During this period, revolutionary technical advances in products were mainly driven by producers, while consumers had a limited impact on the function of the products in the first place. Confronted with this unbalance, while a variety of methods, ranging from safety regulations to product standards, were offered to incentivise producers to internalise the accident cost generated by their activities, these methods are not expected to optimise the producer's level of activity. Firstly, the update of legal texts always falls behind the rate of innovation, which indicates that new activities are out of supervision by the authorities. Secondly, for the activities relating to the plan of production and the intensity of specific activities, such information may be unobservable to consumers and regulators. In the context where machines are driven by codes, the information asymmetry becomes substantial, because the coding activities are entirely under the control of producers.[408] Against this background, the shift from negligence to strict liability is substantially explained as an increasing necessity to control the unobservable activities of producers. In other words, producers are targeted as the "most suitable party" to reduce accident costs in the sector of production. Being subject to strict liability, producers understand that they would bear all the residual risks. Therefore, producers are actually provided with an incentive to optimise their behaviour so as to minimise the accident cost that they would ultimately internalise.

In contrast to producers, we have not yet witnessed a shift to strict liability for downstream suppliers. Compared with producers, who make final products and put them into circulation, suppliers distribute products via their logistics network. While the product could be damaged in the process of transfer, the activities of suppliers do not fundamentally determine the function of the product.[409] Therefore, suppliers simply serve as the successors of the original producers, and their role is auxiliary to the primary activities taken by producers. As the risk generated by the activities of suppliers are significantly lower than those of producers, they are not considered as a more suitable party than producers to reduce the accident. As a consequence, since the deterrence goal can be well accomplished by other instruments (e.g. linear chain of contracts) and strict

[408] Kim, Sunghyo. "Crashed Software: Assessing Product Liability for Software Defects in Automated Vehicles." Duke L. & Tech. Rev. 16 (2017): 300.

[409] See Geistfeld (2011), supra note 232, at 296.

liability shows limited improvement compared to the rule of negligence, suppliers are still subject to the fault-based negligence rule.

To summarise the discussion in this part, strict liability would be desirable in the case where the activity of a party is important and less likely observed or supervised by external parties. In other words, strict liability is superior where contractual parties and regulators fail to embed the relevant obligations into contract or regulations.

7.1.3. Activity level in the context of 3D printing

The analysis above implies that applying strict product liability to producers would be desirable to reduce accidents, given their dominant role in deciding the function of a final product and the observability of their activities.

The extent to which the arguments pro strict liability that are sketched in Section 7.1.2 still hold crucially depends on the exact way in which the production process is organized. The more the different activities are executed by one party, the more it resembles traditional production and the more the arguments will hold accordingly. From this perspective, we may firstly conclude that strict liability is still desirable for the "one-stop" business model. The reasons are, briefly speaking, that in a one-stop model, producers organise all activities, which could be less observable to consumers. In comparison, in the "separation model", the arguments in favour of strict liability on reducing activities are weaker. As a complete production process is undertaken by two separate actors, there is no longer a party whose activity is as dominant as the mass producer or the producer under the "one-stop" model.

Admittedly, according to the technical feature of 3D printing, the digital designing activities under Model A seems to be more critical than the fabrication activities under Model B. For example, under Model A.1 and Model A.2, the quality of the CAD file is nearly fully determined by the digital designer. Consumers and fabricators subsequently can do little to influence the performance of the CAD file through their own behaviour.[410] From this perspective, it seems that controlling

[410] See Kim (2017), supra note 408.

the activities of the CAD file maker would contribute to a significant decrease in accidents.[411] However, this proposition might not prevail considering the complexity of production in 3D printing. To explain, despite the critical role of CAD file designers in reduce accidents under the "separation model", their activities are not the only means to influence accidents. Instead, the activities of consumers as well as fabricators also play a role, which sometimes are even more crucial.

Firstly, the activity level of *consumers* is crucial in specific scenarios. For example, the argument to optimise the activity level of CAD file designers becomes weaker when it comes to Model A.3, in which the preference of consumers would play a role in conceptualising the CAD file. In this circumstance, only offering an incentive to the CAD file maker for optimising the level of activity may not result in the socially optimal outcome. Besides, the activities of consumers are important under the separation models, since they can influence the cost of an accident in a way that they serve as the party to coordinate the process of production. Under separation models, consumer needs to firstly choose the source of the CAD file and then to decide the 3D printing service provider. This decision is determined by the consumer in a way that is based on the comparison between the utility and cost of specific combination, which can hardly be observed by outsiders. Suppose a first scenario, where a consumer may choose to get a CAD file from a professional designer (i.e. under Model A.3) and then have it printed out by a professional fabricator (e.g. under Model B.1). Then suppose a second situation, in which a consumer may choose a CAD file from an online marketplace (i.e. under Model A.2) and subsequently take it to a non-professional (i.e. under Model B.2). Comparing the two scenarios above, it seems that the second scenario would pose more risk than the first one. In this case, offering consumers an incentive to make a choice

[411] Many literatures articulated that it is the developer of the software that should internalise the accident cost. For example, as Gurney argued, "the primary purpose of products liability is to ensure that manufacturers put reasonably safe products on the market by holding them liable for harm caused by defective products they place into the marketplace." Since "manufacturer writes and controls the algorithm for the autonomous technology", "the easiest method for courts to ensure autonomous vehicle safety would be to hold the manufacturer liable for accidents caused in autonomous mode". See Gurney (2013), supra note 378, at 271-272. Similar arguments can be seen in Butler, Alan. "Products liability and the internet of (insecure) things: Should manufacturers be liable for damage caused by hacked devices." U. Mich. JL Reform 50 (2016): 913; Hurwitz, Justin. "Cyberensuring Security." Conn. L. Rev. 49 (2016): 1495. Similar arguments can also be found in 3D printing literature. See, for example, Lindenfeld, Eric. "3D Printing of Medical Devices: CAD Designers as the Most Realistic Target for Strict, Product Liability Lawsuits." UMKC L. Rev. 85 (2016): 79; see also Sharpe, Mika. 2019. "Products Liability in the Digital Age: Liability of Commercial Sellers of Cad Files for Injuries Committed with a 3d-Printed Gun ." American University Law Review 68, no.6: 2297-2336.

diligently is also of great importance. Making a CAD file designer bear the risk posed by subsequent activities is inefficient, because s/he is not the most suitable party to take effective measures to deal with those risks.

Secondly, apart from the consumer's activities, the activity level of fabricators also plays a role in reducing accidents. In a case that the CAD file is designed by a professional entity but it is subsequently printed out by a non-professional individual, the need to control the activity of the fabricator becomes critical. In other words, in the aforementioned case, besides providing the digital designer with an incentive, it is also necessary to offer the fabricator an incentive to optimise the activity.

In brief, when production is organised in a way that the digital designing and physical fabrication are separately taken by the parties from different entities and that consumers serve as the coordinator of the involved parties, it is hard to identify the "most suitable party". In other words, the answer is not clear when it comes to the questions of whose activity is considered to be more dangerous and who can reduce the cost of the accident at the cheapest cost. Under separation models, liability rules can no longer achieve the goal of deterrence by targeting a single party. While CAD file designers seem to be the most suitable party, the activities of consumers and fabricators may derogate this expectation to a large extent. In the end, the analysis may disappoint the justification of strict liability in terms of its function in improving the effect of deterrence by optimising the activity level of relevant parties.

7.2. Product liability from the perspective of information problems

One obstacle that prevents the risk from being optimally allocated via bargaining is the asymmetric information between the producer and consumers.[412] If a consumer misperceives the risk of a product, s/he would not accurately compare the full cost of the product with the utility gained from it. As a result, the consumption made by consumers will not reflect their real demands. In the market, the price mechanism is one of the most critical instruments which the consumers rely on to make decisions. If the price can accurately reflect the actual safety of a product, consumers are expected to make right decisions, which might be consistent with the socially optimal outcome.

[412] See the discussion in Section 4.2.

In the realm of tort liability, the full price can be disclosed through specific liability rules.[413] It has been argued in the literature that if the consumer has imperfect information on the safety of the product, strict liability (with a negligence defence) is superior to the rule of negligence because it enables the imperfectly informed consumer to make a choice that corresponds to the socially optimal outcome.[414] This section firstly gives a brief exposition of the signalling function of strict liability for product risk. Then it examines the extent to which this proposition still holds in the context of 3D printing.

7.2.1. Product liability as a way of disclosing product risk: a theoretical approach

In the Law and Economics literature, tort law is studied in its capacity to provide desirable behavioural incentives, both for deterrence purposes and for risk spreading. When analysing product liability from this perspective, the starting point is the hypothetical situation where the consumer is fully informed about the risks of the products s/he is buying. In such a situation of full information, the consumer does not only look at the market price of a product, but also at the expected losses that this product may cause and which are not covered by liability of the manufacturer. The consumer therefore looks at the 'perceived full price', which is determined by market price and expected losses.[415] As modelled previously, the full price at which consumer decision-making can be socially optimal is determined as follows:

$$P = c + wx + zy + wzp(x,y)D$$

Because of the assumption of complete information, the consumer exactly knows what this perceived full price is and s/he will choose the product with the lowest perceived full price. In such a situation, it is not relevant whether the producer can be held liable and whether strict liability or

[413] See See Spence (1977), supra note 242; Epple and Raviv (1978), supra note 227; Polinsky and Rogerson (1983), supra note 231.

[414] Keeton, W. Page. "Products Liability--Inadequacy of Information." Tex. L. Rev. 48 (1969): 398; Daughety, Andrew F., and Jennifer F. Reinganum. "Products liability, signaling and disclosure." Journal of Institutional and Theoretical Economics JITE 164, no. 1 (2008): 106-126.

[415] See Oi (1973), supra note 206.

negligence applies. After all, only if the producer takes the optimal precautionary measures will the perceived full price be minimal. A producer that takes inadequate care but is not liable for this can offer the product against a lower market price, but the consumer will add relatively high expected accident losses, so that the perceived full price will exceed that of a producer who took the desired measures.

In reality, consumers do not possess full information. If they overestimate the risks of the product, they overestimate the perceived full price.[416] As a result, they buy too little of the product and they take too much care in handling the product (as compared to the socially optimal decisions which they would take if they had full information). If they underestimate the risks, the opposite situation occurs.

If the producer is subject to the *rule of negligence*, it will not bear any liability given that it takes the appropriate level of care. The consumer will, in the end, bear the residual risk (i.e., the expected harm $wzp(x,y)D$). In this circumstance, the producer has no incentive to include the expected harm into the market price, since disclosing this part of the cost and investing to optimise the activity level thereof will not be perceived accurately by the consumer. In other words, under negligence rules, any further disclosure of the cost of the product cannot be rewarded by a competitive advantage in the market. Provided that consumers underestimate the expected damage caused by the product, s/he may assess the full price of the product lower than it should be. As a result, too many products would be consumed. Apart from the overconsumption, given the due care level, the producer would be induced to increase the intensity of activities. In this regard, we can imagine that excessive risky activities that are not identified within the level of care would be undertaken by the producer.

The outcome will be different if *strict liability* applies to the producer. Under strict liability, the producer serves as the residual risk bearer, which means that unless the consumer commits contributory negligence, the producer will have to bear all the costs caused by the product. In this case, the producer will include the expected harm in the market price.[417] Therefore, under the

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[416] See See Spence (1977), supra note 242; Epple and Raviv (1978), supra note 227; Polinsky and Rogerson (1983), supra note 231.

[417] Daughety, Andrew F., and Jennifer F. Reinganum. "Product safety: liability, R&D, and signaling." The American Economic Review (1995): 1187-1206; Daughety, Andrew F., and Jennifer F. Reinganum. "Economic analysis of

regime of strict product liability, the market price of a product would equal to full price. As all the costs that are not generated by the consumer can be shown via the market price, the consumer does not need to employ other instruments to assess the amount of such costs. Hence, compared with the rule of negligence in which the consumer still needs to rely on extra information to make the appropriate choice, by linking product risk to the price mechanism, the regime of strict product liability significantly improves the accuracy of consumer's decision-making.

More importantly, the improved decision-making by consumers will have a substantial impact on the behaviour of the producer. To explain, as consumers are less likely to overestimate or underestimate the full price of the product with the adoption of strict liability (with a contributory or comparative negligence defence), they do not tend to buy an insufficient or excessive number of products. In addition, as the full price of the product will be reflected in the market price, producers have an incentive to behave appropriately by optimising their level of care as well as the level of activity. As a result, as any reduction in the accident cost will be perceived by imperfectly informed consumers, diligent producers will be rewarded with a competitive advantage in the market.

7.2.2. The disclosure of information through product liability in the context of 3D printing

The analysis above shows that, in general, as a result of imposing strict liability on producers, consumers are better placed to evaluate their utilities and the potential cost of the product, which ultimately leads to a socially optimal amount of consumption. This subsection explores the extent to which this proposition still holds with 3D printing and, more importantly, how the adoption of 3D printing challenges this traditional justification.

The "most suitable party" of disclosing the full cost of production is missing

At first glance, the information disclosure function of strict liability may still play a role under the "one-stop model", where there is an entity handling the whole process of manufacturing. By imposing strict liability on this entity, it is expected to conclude the market price as the full cost of

products liability: theory." In Jennifer Arlen (ed.) RESEARCH HANDBOOK ON THE ECONOMICS OF TORTS. Edward Elgar Publishing 2013, at 69-96.

production. However, this justification may not hold in the circumstance where production is arranged under the "separation" model. Under the separation model, as the digital modelling and fabrication are undertaken by the parties from two different modules, each of them may hold the information only to the extent of their own activities. In this regard, it might be difficult to decide whether it is the CAD file designer or the final fabricator that has the ability to accurately assess the full price of the final product. Therefore, if we abruptly impose strict liability on either of the involved parties, they may fail to indicate the full price of a product through market price.

The dilemma aforementioned can be explained in the following two cases.

Firstly, in a situation where the consumer obtains a CAD file from a non-professional designer (e.g. under Model A.1 or A.2) and then it has the CAD file printed out by a professional fabricator (e.g. under Model B.1 or Model B.3), while the fabricator is professional that is supposed to be more knowledgeable than any other actor along the supply chain, it faces an information asymmetry regarding the safety of the CAD file. In other words, in this circumstance, since the CAD file designer may possess more concrete safety information than the fabricator, placing strict liability onto the latter party may not help to indicate the full price to the consumer.

In another situation, a consumer may choose to purchase a high-quality CAD file from a certified professional designer (e.g. under Model A.3), but then s/he has it printed out by a non-professional fabricator using the most basic desktop 3D printer (e.g. under Model B.2). In such a situation, applying strict liability to the CAD file designer does not make any sense from the economic perspective. It would be very difficult or even impossible for the CAD file designer to make an accurate assessment of the risk that is posed due to (low-quality) printing.

In either of the two circumstances aforementioned, if one of the involved parties is strictly liable for the damage caused by the final product, it would not only have to include the full cost of its activities into the final market price, but also have to estimate the expected damage caused by the other. Due to the existence of information problems, the best this party can do is to include an assessment of the 'average costs' in the price. This may result in the well-known problem of adverse selection, because the price set by the party cannot differentiate between low-quality and high-quality of the other party.

Strict liability may not reveal the full cost to consumers

Under separation models, if the party who has the best information cannot be easily decided, in order to assess the full price of the product the consumer may have to collect information separately from the CAD file designer and the fabricator. The previous analysis has shown that accessing information could be easier in specific business models (e.g. through Model A.3, Model B.1 and Model B.3), but more difficult in others (e.g. under Model A.1, Model A.2 and Model B.2). Under this background, the issue to be further discussed is: whether tort liability would help disclose the information in the scenario where contractual liability fails.

Theoretically, if both the CAD file maker and the fabricator are subject to strict liability for the damage caused by their defective "products", since they serve as the party to bear the residual liability they would have an incentive to include the full cost of their activities into the market price. By doing so, consumers can expect the full price of the final product by adding up the two full prices offered by the CAD file maker and the fabricator. In reality, however, this mechanism may frustrate the consumer in the end. The reasons are twofold. Firstly, there is not a price mechanism that a consumer can rely on to assess the full cost of a CAD file, if a consumer chooses to obtain the CAD file from an open-source platform (i.e. under Model A.1). In this regard, even if strict liability applies to the CAD file makers under Model A.1 and these parties are also incentivised to behave appropriately, the full cost that is determined by different CAD files makers cannot be accessed by the consumer via market price. A consumer thereby may choose a sophisticated design with higher risks which, given perfect information, would not be chosen by him/her.[418] Secondly, for the circumstances where information may not be well revealed to consumers (i.e. in Model A.2 and Model B.2), as the actors on these business models are ordinary individuals, they may not have a better capacity than consumers in terms of evaluating the probability of an accident or the real scale of damage.[419] As a result, the market price offered within these business models may deviate from the full cost.

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[418] Hylton, Keith N. "The law and economics of products liability." Notre Dame L. Rev. 88 (2012): 2457.

[419] From the perspective of information, non-professional individuals cannot compete with traditional mass producers. For example, Professor Owen demonstrated that "manufacturers have a powerful hold over the means for discovering and correcting product." He further explained that this is because "through the processes of design, testing, inspection and collection of data on product safety performance in the field, the manufacturer has virtually exclusive access to much of the information necessary for effective control of dangers facing product consumers." See Owen, David G. "Punitive damages in products liability litigation." Michigan Law Review 74, no. 7 (1976): 1257-1371.

Summary

Strict liability, in theory, ensures that the accident cost can be captured in the price mechanism, so that the market price serves as a credible signal to the consumer by showing the full cost of the product. However, the analysis in this subsection finds that this proposition could be diminished in the context of 3D printing, especially when production is organised under "separation models".

On the one hand, unlike traditional manufacturing where we can find a party who is best positioned to observe the full cost, this "most suitable actor" cannot be easily decided in the context of 3D printing. In other words, we cannot expect one party to reveal the full cost through market price by imposing strict liability on it.

On the other hand, applying strict liability separately to CAD file makers and fabricators to the extent of the damage caused by their defective "products" may fail to reveal the full cost to consumers in the end. In particular, in the scenarios where contracting over risk suffers information problems the most (e.g. under Model A.1, Model A.2 and Model B.2), imposing strict liability to relevant actors does not promise to remove all information asymmetries.

7.3. The efficiency of liability rules in the event of legal uncertainties and errors

Unlike contracting for product risk, in which contractual parties are supposed to find the socially optimal outcome by their own efforts, in tort liability parties are incentivised by liability rules, and whenever harm occurs, they may go to the courts to settle the dispute. Hence, in tort liability, courts play an important role in achieving the socially optimal outcome.

Unfortunately, errors usually are unavoidable in deciding a case since the courts always rely on the proof provided by the parties to evaluate the elements, and judges have to make a great effort to find the facts and to interpret the rules.[420] The required elements under various liability rules are different. In general, a court has to decide the level of care, the magnitude of liability (i.e., damage)

[420] Ogus, Anthony. "Information, error costs and regulation." International Review of Law and Economics 12, no. 4 (1992): 411-421; Kaplow, Louis, and Steven Shavell. "Accuracy in the Determination of Liability." The Journal of Law & Economics 37, no. 1 (1994): 1-15; Dari-Mattiacci, Giuseppe. "Errors and the functioning of tort liability." Supreme Court Economic Review (2005): 165-187.

and the scope of liability (i.e., causation) under the negligence rule. In contrast, in the regime of strict liability, finding the care level is not required. A court may make mistakes in finding and assessing these elements. In general, the mistakes can be categorised into two types: they may be random mistakes, which relevant parties cannot expect; they may be systematic mistakes, which means that parties can anticipate the result even before they go to court.

The analysis of law and economics indicates that uncertainties and errors could have significant impact on the behaviour of relevant parties. Currently, no literature has uncovered how the behaviour of relevant parties could be influenced by the possible uncertainties and systematic errors that are generated when applying tort liability in the context of 3D printing. The discussion in this section will contribute to this topic.

7.3.1. Uncertainties and errors in the finding of negligence

Compared with negligence, strict liability does not require the plaintiff to prove the fault of the injurer. Strict liability, therefore, by its nature, is superior to negligence since it saves the costs of finding negligence in litigation.[421] In practice, if the court can precisely find and decide the due care level in correspondence with the optimal care of level, injurers will be induced to optimise their level of care. However, in reality, the decision made by the court may deviate from this optimality. Uncertainties and systematic errors can occur in the court finding of negligence; in these situations, the incentive of the parties to behave appropriately might be distorted.

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[421] See Epstein, Richard A. "A theory of strict liability." The Journal of Legal Studies 2, no. 1 (1973): 151-204; see also Cooter, Robert, and Thomas Ulen. 2016. LAW AND ECONOMICS (6th edition). Addison-Wesley, at 218. However, it must be noteworthy that in bilateral precautions, where strict liability is always accompanied by a defence of contributory or comparative negligence, the superiority of strict liability might be diminished. See Shavell (2009), supra note 212, at 84-85.

Economic analysis

Courts may make *random* mistakes in the finding of negligence. To explain, uncertainties could arise when the court errs in assessing the true care level[422], due care level[423] or momentary care level[424] taken by the injurer. In either of the three scenarios, where parties sense that the incidents could be randomly decided, they will be induced *to take a higher level of care and to reduce the level of activity accordingly.*[425]

Apart from the uncertainties in the finding of negligence, the court may also make *systematic* errors in deciding the due care level and the optimal care level. Two possibilities exist. Firstly, had the authority systematically underestimate the optimal care level and thereby set the due care level lower than optimality, the injurer would be induced to comply with this due care level.[426] Secondly, if the authority systematically overestimates the optimal care level and thereby sets the due care level higher than optimality, the injurer will be induced to comply with the due care level.[427] In brief, no matter in which direction the due care level is wrongly decided, *the injurer will ordinarily be motivated to take this wrongly decided due care level rather than the optimal level*.[428]

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[422] This takes place as the court may sometimes mistakenly decide that the true care level taken by a party is higher or lower than the due care level, when that is not the case. See Kaplow and Shavell (1994), supra note 420; Shavell (2009), supra note 212, at 79-80.

[423] The court may either overestimate or underestimate the due care level in a particular case. See Shavell (2009), supra note 212, at 81-82.

[424] In a specific activity, a party could behave appropriately most of the time, but may not maintain this level of care all the time. This implies that the party has to run the risk of being found negligent. See Shavell (2009), supra note 212, at 82.

[425] See Craswell, Richard, and John E. Calfee. "Deterrence and uncertain legal standards." JL Econ. & Org. 2 (1986): 279; Schäfer, Hans-Bernd, and Frank Müller-Langer. "Strict liability versus negligence." In Boudewijn Bouckaert and Gerrit de Geest (eds.) ENCYCLOPEDIA OF LAW AND ECONOMICS. VOLUME II. CIVIL LAW AND ECONOMICS. Edward Elgar Publishing Limited, 2000. 597-624, at 617-618; see also Shavell (2009), supra note 212, at 82. For the case where a strict liability with a defence of contributory or comparative negligence is adopted, uncertainties in finding the negligence of the consumer will lead him/her to take a higher level of precaution and to reduce the activity level. See Shavell (2009), supra note 212, at 84-85.

[426] For example, if a manufacturer finds that the standard that was adopted in previous cases by the court does not require the manufacturer to install a device, it will not install the device.

[427] For instance, if the manufacturer finds that the court in previous cases adopted a higher standard, which includes unnecessary precautionary efforts, it will be induced to respect this higher standard unless the cost of compliance is even higher than the expected harm.

[428] See Shavell (2009), supra note 212, at 83. Literature shows that the distortion of behaviour due to the systematic errors of courts can be reduced by shifting a comparative negligence rule. In this rule, by sharing the losses between

The analysis in this part implied that uncertainties and systematic errors in the finding of negligence could distort the optimal deterrence effect. However, the extent to which these uncertainties and errors matter rests on the specific context.[429]

7.3.2. Uncertainties and errors in determining causation

The meaning of causation from the perspective of law and economics

Early literature does not make an explicit distinction between causation and efficient prevention.[430] If an injurer is regarded as the lowest cost avoider in an accident, it is also considered as the party that causes the accident. In this regard, causation is simply a result of the assessment of efficiency rather than a preliminary criterion to evaluate liability.[431] As Professor Ben-Shahar summarised, in the early literature, "inefficient behaviour is synonymous with causing an expected harm."[432] Later, the meaning of causation was explained from the perspective of prospective-probability. In this dimension, causation turns out to be an element that determines the *scope* of liability. Liability is applicable only if an action by a party increases the probability of harm.[433] By linking causation with the *probability* of an accident, the scope of liability is restricted to the situation where an incremental action has raised the expected harm. This approach, therefore, is distinguishable from the "but-for" approach, in which we are concerned more about whether the accident would not have occurred without the action but less about whether there are still some situations in which the

the parties, fewer distortions on the behavior of parties can be resulted. See Cooter, Robert D., and Thomas S. Ulen. "An economic case for comparative negligence." NYUL Rev. 61 (1986): 1067.

[429] See Shavell (2009), supra note 212, at 82-83.

[430] The implicit status of causation in tort law is partly resulted by the insight of Coase, who argued that the essence of harm is reciprocity. See Coase (1960), supra note 8. A similar thought was also shared in Calabresi, Guido. "Some thoughts on risk distribution and the law of torts." The Yale Law Journal 70, no. 4 (1961): 499-553.

[431] Landes, William M., and Richard A. Posner. "Causation in tort law: An economic approach." The Journal of Legal Studies 12, no. 1 (1983): 109-134.

[432] Ben-Shahar, Omri. "Causation and foreseeability. In Boudewijn Bouckaert and Gerrit de Geest, (eds.) ENCYCLOPEDIA OF LAW AND ECONOMICS VOLUME II. CIVIL LAW AND ECONOMICS, Cheltenham, Edward Elgar, 2000, 644-668, at 646. See also Brown (1973), supra note 396.

[433] Shavell, Steven. "An Analysis of Causation and the Scope of Liability in the Law of Torts." The Journal of Legal Studies 9, no. 3 (1980): 463-516.

action raises the probability of the accident. In other words, adopting the standard of prospective-probability significantly improves the restriction of the scope of liability.[434]

Since the scope of causation is generally correlated with the level of care *in the rule of negligence*, it is sometimes difficult to isolate these two elements from a terminological perspective and to delineate the boundary of the causation and care level in the application. In theory, the difference between care level and causation is significant, so causation deserves to be an independent term in evaluating liability rules.[435] To illustrate, the optimal care level is determined by comparing the *cost* with the *benefit* of precaution. The optimal care level is found at the last point, where an extra investment on precaution is smaller than the harm it reduces. In other words, even though there are some situations where causation is inappropriately limited or unlimited, the finding of the optimal care level would not be influenced. In comparison, as mentioned, causation is linked to probability, so that causation is optimally found at the point where an activity can still probabilistically influence the damage.[436] In this sense, the importance of causation is that if a party is found to be negligent, it should only compensate for the losses that were caused by its behaviour and not all the losses.[437]

In theory, there are two situations in which causation is not optimally determined. Firstly, causation could be overly restricted, in which there are circumstances where the action of a party raises the probability of harm, but the party is ultimately found not to be liable. Secondly, causation could be inappropriately unrestricted, in which there are circumstances where the action of a party does not raise the probability of harm, but the party is found liable. This latter situation also represents the mistakes made in *traditional* economic models of the negligence rule. In this sense, the

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[434] See Shavell (1980), supra note 217.

[435] See Dari-Mattiacci (2003), supra note 213.

[436] Wright, Richard W. "Actual causation vs. probabilistic linkage: The bane of economic analysis." The Journal of Legal Studies 14, no. 2 (1985): 435-456.

[437] Grady, Mark F. "A new positive economic theory of negligence." The Yale Law Journal 92, no. 5 (1983): 799-829. See also Kahan, Marcel. "Causation and incentives to take care under the negligence rule." The Journal of Legal Studies 18, no. 2 (1989): 427-447; Marks, Stephen. "Discontinuities, Causation, and Grady's Uncertainty Theorem." The Journal of Legal Studies 23, no. 1 (1994): 287-301.

traditional model wrongly shows that the cost, which would have arisen even if the party was diligent, should also be paid by the injurer.[438]

Therefore, under the rule of negligence, combining the consideration of the requirement for care level and the scope of liability, if an injurer is found negligent, the amount of compensation should be limited only to the extent that the harm is "caused" by the injurer, but not to the extent that would have occurred anyway had the injurer been diligent.

Economic analysis of systematic causal errors

In many situations, the court can make systematic errors in determining causation, and these errors can be anticipated by the parties prior to the accidents. This section discusses how these errors, which are made by the court in the determination of the scope of liability, influence the behaviour of relevant parties. In addition, the extent to which the distorted behaviour diminishes social welfare (i.e., the care level and activity level) is also analysed.

Given the errors in determining causation, the influence on deterrence could be largely determined by the difference between strict liability and the rule of negligence.

In the regime of strict liability, if the scope of liability is *too restricted*, which means there are still some circumstances where harm is caused by the actions of injurers but these actions are not counted as the necessary causation, the injurer would underinvest in precaution and undertake excessive activities.[439] On the other hand, if the scope of liability to some extent is *unrestricted*, in which circumstances the injurer is held liable in some situations, wherein their actions do not cause the harm, the injurer will be induced to take the *optimal care level*, but its level of activity will be *limited*.[440]

[438] This mistake was firstly found and argued by Grady. See Grady (1983), supra note 437; see also Kahan (1989), supra note 437. For an overview of the traditional model, see Posner (1972), supra note 396.

[439] See Ben-Shahar (2000), supra note 432, at 649.

[440] The restricted activity level of injurer, which is resulted from unrestricted causation, is also called the "crushing" effect. In the scenario of production, a crushing effect will lead producers to reduce their investments on innovation. See Shavell (1980), supra note 433. See also Shavell, Steven. "Uncertainty over causation and the determination of civil liability." The Journal of Law and Economics 28, no. 3 (1985): 587-609.

Under *negligence*, the effect of deterrence relating to errors in finding the causation is also heavily influenced by the errors in the finding of negligence. *Given that the court can precisely find the optimal care level*, the determination in causation, restricted or unrestricted, has a limited impact on distorting the behaviours of the injurer.[441] In reality, unrestricted causation has already been assumed in the traditional model of negligence.[442] This imperfect negligence regime is not considered a critical problem in the literature since, as analysed previously, this unrestricted causation will not distort the incentive of injurers to take the optimal care level.[443] However, it should be noted that the finding of the negligence rule so far is based on the *assumption* that due care level is correctly determined to be the same as the optimal care level by the court.[444] Assuming that courts make errors in finding the negligence, injurers will behave differently between the situation in which causation is unrestricted (i.e., the traditional model) and the situation in which causation is optimally restricted (i.e., the model advanced by Grady). Specifically, in the circumstances where the court under- or overestimates the optimal level of care, setting causation in an *unrestrictive way* (as observed under the traditional model) would induce injurers to take this due care level.[445] In contrast, in the scenario where the court is able to optimally restrict the causation, even if the court set up a due care level higher than the optimal one, the injurer would still be incentivised to take optimal care level.[446]

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[441] See Grady (1983), supra note 437. Under the rule of negligence, from the perspective of care level, the injurer will escape liability once it complies with the due care level. In this sense, the error in determining causation, restricted or unrestricted, will not alter the incentive of injurers to take this due care level.

[442] A discontinuity on the cost borne by the injurer is found on the margin where due care level is taken. See Grady (1983), Grady (1983), supra note 437. See also Marks (1994), supra note 437.

[443] See Landes and Posner (1983), supra note 431.

[444] In Grady's argument, he assumes that the court holds perfect information, and it can correctly determine the due care level at the level of optimality. See Grady (1983), supra note 437. Kahn, in his paper, relaxed this perfect information assumption and discussed how the behaviour of parties could be further influenced. See Kahan (1989), supra note 437. See also Hylton, Keith N. "Information and Causation in Tort Law: Generalizing the Learned Hand Test for Causation Cases." Journal of Tort Law 7, no. 1-2 (2014): 35-64.

[445] In this regard, whenever causation is unrestricted: if the court underestimates the optimal care level, the injurer will be induced to invest less precaution; if the court overestimates the optimal care level, the injurer will be induced to take excessive precaution.

[446] As stated by Kahan, "even if due care exceeds optimal care, injurers will exercise optimal care once restrictions based on causation are taken into account." See Kahan (1989), supra note 437, at 432-433.

To conclude this part, considering the possibility that courts may make errors in finding the optimal care level and the scope of liability, applying different liability rules may provide producers with different incentives.

Firstly, if the optimal care level is accurately found by the court, even if the scope of causation might be unrestricted, applying negligence rule or strict liability can both incentivise the producer to take the optimal care level.

Secondly, given that the court cannot accurately set the due care level at the optimal care level, but it can optimally restrict the scope of liability, strict liability will incentivise producers to take the optimal care level, because they have to bear the accident cost in the end. Fault-based rules can also induce producers to optimise the level of care in this scenario, conditioned that a relatively higher due care level is implemented.

Thirdly, if the court fails to set the due care level at its optimality and meanwhile it tends to unrestrict the scope of liability, producers are expected to *optimise* their precaution under strict liability. In contrast, producers will choose to take the *due care level* if they are subject to fault-based rules.

Economic analysis of causal uncertainties

Apart from the systematic errors made by the court, the court can also make errors *randomly*.[447] For example, for particular harm, with limited knowledge of the state of art, the court may have no idea whether a specific party caused the damage. In these circumstances, the court has to employ concrete methods to assess whether the party "caused" the damage. In general, two types of rules are developed in practice. One is called the *threshold probability rule*. When subjected to this rule, the injurer has to bear the liability to the full extent if the probability of the injurer's action is considered to be higher than a determined threshold.[448] The other is called the *proportionate*

[447] See Kaplow and Shavell (1994), supra note 420.

[448] The threshold probability rule is a kind of "all-or-nothing" rule. For example, if a law decides that a party is liable provided that his action had a probability of 50% to result in the accident, then a party whose action is assessed 51% probability with the accident will have to bear all the liability. In comparison, a party with a 49% probability will escape the liability.

liability rule, under which different parties would share the liability when the court is uncertain about causation.[449]

From a law and economics perspective, while the threshold probability rule promises a better effect on compensation, the proportionate liability rule can provide injurers with a greater incentive to behave appropriately.[450] When the court applies the *threshold probability rule* to deal with causal uncertainties, it might err in determining the threshold. If the court sets the threshold systematically higher than the actual probability of causation, then the injurer will be incentivised to lower the care level and to undertake excessive activities no matter whether the injurer is subject to strict liability or negligence, because the probability of causing the accident is not well captured in liability.[451] In another instance, if the court sets the threshold systematically lower than the actual probability of causation, the injurer will be incentivised to take excessive care and to shrink activities under strict liability. In comparison, under the negligence rule, the injurer will maintain the optimal care level and activity level.[452] In contrast to the threshold probability rule, the *proportionate liability approach* could result in the socially optimal deterrence not only under strict liability but also under the rule of negligence.[453]

To conclude the analysis in this part, confronted with causal uncertainties, the proportionate liability rule shows better performance compared to the threshold probability rule. Strict liability and negligence elicit no significant difference in terms of socially optimal deterrence.

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[449] The most common proportionate liability rule is to share the liability on the basis of their market share. See Rose-Ackerman, Susan. "Market-Share Allocations in Tort Law: Strengths and Weaknesses." The Journal of Legal Studies 19, no. S2 (1990): 739-746.

[450] The threshold probability rule promises a better result than the proportionate liability rule from the fairness perspective. Firstly, it is perceived to reduce causal uncertainties by motivating plaintiffs to invest more in evidence. In contrast, under proportionate liability rule, since the plaintiff will get compensation anyway, s/he has no motive delineate causation. Secondly, litigation cost is found significantly lower under the threshold probability rule than that in proportionate liability rule. See Levmore, Saul. "Probabilistic recoveries, restitution, and recurring wrongs." The Journal of Legal Studies 19, no. S2 (1990): 691-726. See also Shavell (2009), supra note 212, at 115-117.

[451] See Shavell (2009), supra note 212, at 115.

[452] Ibid.

[453] See Shavell (2009), supra note 212, at 116.

7.3.3. Uncertainties and errors in determining damage

If the tortfeasor is liable for an accident, s/he should compensate the victim as if the accident had not occurred. The magnitude of the liability that is expected to be taken is called the damages.[454] One crucial assumption is made that the court can find the exact amount of damages. However, due to the lack of information, two undesirable instances could occur in the evaluation of damages. On the one hand, the court might only determine damages accurately on average but not on a case-by-case basis. On the other hand, the court may systematically over- or underestimate the magnitude of liability in an individual case. The errors by the court in deciding damages not only relate to the fairness of compensation but, more importantly, they have a significant impact on the effect of deterrence.

Economic analysis

The court may be uncertain about the level of loss in a specific accident. In this scenario, if the court is able to determine the damages correctly *on average*, then the optimal deterrence provided to the injurer will not be distorted.[455]

However, while the court may accurately estimate the magnitude of liability on average, the compensation to victims may be inaccurate *in individual cases*. If injurers anticipate these errors, they may be induced to behave inappropriately. In particular, under strict liability, tortfeasors will internalise the total costs (including the harms) no matter whether they are diligent or not. If the damages are determined to be higher than the harm they caused, then tortfeasors will be induced to take additional care in order to optimise the excessive damages. If the damages are determined to be lower than the harm caused, then tortfeasors will be induced to take less care accordingly.[456] In comparison, under the rule of negligence, victims will be compensated only if tortfeasors are

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[454] Visscher, Louis. "Tort damages." in Faure, Michael (ed.), TORT LAW AND ECONOMICS. Vol. 1. Edward Elgar Publishing. 2009, p.153-200.

[455] See Shavell (2009), supra note 212, at 131-132.

[456] In other words, when strict liability applies, the decision on precaution is affected by the over- or under-estimation of damages in the same direction. See Cooter and Ulen (2016), supra note 421, at 218.

negligent. Any under-assessment or over-assessment of the level of loss will not change the incentive of the tortfeasor to take optimal care.[457]

Whether the court should make every effort to determine the magnitude of liability accurately is a controversial topic. In theory, this issue relates to two problems. Firstly, the reduction of inaccuracy is at the expense of an increase in administrative costs. Only if an extra investment could result in a more efficient outcome, would the effort be desirable.[458] Secondly, if the injurer ex-ante can only expect the magnitude of liability on average but not the exact anticipated errors in his case, then determining the damages on average will not result in any distortion of deterrence.[459] In other words, a precise assessment ex-post does not improve the behaviour of the parties given their poor evaluation of the magnitude of liability. This situation is not unusual in reality since the parties usually have no exact idea of the magnitude of liability at the time when their behaviours lead to an accident.

To conclude, if courts can decide damages accurately on average, producers would still be incentivised to take the optimal level of care under either negligence or strict liability. However, given errors in finding the magnitude of liability in the individual case, negligence rule is superior to strict liability by inducing producers to optimise the level of care.

7.3.4. Court errors and the effect of deterrence: a preliminary summary of findings

Before going in-depth into the context of 3D printing, it is necessary to summarise the theoretical implications that have been analysed so far.

The discussion above indicates that strict liability and fault-based rules are sensitive to legal errors in different respects. In general, the deterrence effect under the regime of strict liability is sensitive to the assessment of damages. Given that the magnitude of liability can be accurately decided by the court, even if causation is unrestricted to some extent, applying strict liability to producers

[457] It is noticed that this proposition is held only if the errors made by the court are moderate. If the court underestimates the damage significantly, then the injurer may be induced to lower his care level. See Cooter and Ulen (2016), supra note 421, at 219.

[458] See Shavell (2009), supra note 212, at 132.

[459] Kaplow, Louis, and Steven Shavell. "Accuracy in the Assessment of Damages." The Journal of Law and Economics 39, no. 1 (1996): 191-210.

would incentivise producers to take optimal care level. In comparison, if the fault-based rules apply, whether producers could be offered the incentive to optimise their precautions is determined by the issue of whether the optimal care level can be precisely found by the court and/or whether the scope liability could be optimised. Particularly, if the court is able to set the due care level accurately the same as optimal care level, producers will be incentivised to take this optimal care level. If, however, the court errs in deciding the care level, whether producers would be incentivised to optimise their care level is determined by the ability of court to find causation: (a) given that the scope of liability can be precisely determined, by setting up a higher precautionary level, producers would still be induced to take optimal care level; in contrast, (2) given that the court can also hardly find the scope of liability in a precise way, the consumer would be incentivised to take the due care level, which may be higher or lower than optimality.

To conclude, the analysis so far seems to indicate that, given the existence of court errors, applying strict liability has a better chance to incentivise producers to take optimal care level. However, it must be noted that such a conclusion is based on many additional assumptions.

First and foremost, the preliminary conclusion is based upon the assumption that producers do not suffer the *insolvency* problems. In addition, the analysis so far assumes that the accident is more or less unilateral, so that optimising the incentive of producers is far more important than consumers. This implies that, when the efficiency of various liability rules could be distorted by court errors, we must choose the liability rule in which the incentive offered to producers could be optimised or least influenced. In reality, if consumers also play an essential role in affecting the accident cost, in which sense that accident is not caused by the "defect" on the producer's side but by non-defective behaviours from consumers, consumers should be seen as the most suitable actor that should be offered the incentive. Accordingly, the impact of court errors on the deterrence effect on consumers becomes more important. Whether the behaviour of consumers has a considerable impact on accident should be examined in specific scenarios. In a circumstance where consumers can also substantially contribute to accidents, strict liability always applies with a defence of contributory negligence or comparative negligence, which enables producers to (partly) get rid of bearing liability provided that consumers fail to take due care level. Therefore, when examining the extent to which court errors distort the efficiency of strict liability in a bilateral accident, their impact on the incentive of consumers should also be considered.

7.3.5. Evaluating the theoretical implications in the concrete context of 3D printing

Having shown how court errors could influence the deterrence effect, the purpose of this subsection is to explore these theoretical implications for the context of 3D printing.

Finding negligence in the context of 3D printing

The first question to be asked is whether the optimal care level can be precisely found in the context of 3D printing. To answer this question, we need to evaluate the extent to which courts, as well as other authorities who help to establish the due care level, can precisely decide the optimal care level.

In modern production, as regulators and standard setters cooperate closely with experts and producers in specific sectors, their knowledge of the state of art has improved significantly. As a result, the determination of the due care level has an increasing chance to be assessed at the optimal care level on average. However, despite correct on average, these measures may omit the divergence between producers to a large extent and thus place them under the same umbrella. This situation causes anticipated errors in individual cases. For some producers, the determined due care level is somewhat high; as a result, particular precautionary measures may be overly burdensome for their simple, functional products.[460] In this sense, heavy burdens to take precaution will be exerted on this group of producers. In comparison, for other producers who develop more complex products that also run a higher level of risk, the predetermined regulations and standards may be set systematically low. This anticipated lower level of due care may induce producers with sophisticated and functional products to reduce their precautions.

In reality, the courts have a chance to correct this problem. By evaluating the due care level in each individual case, the court may determine how to ensure that the due care level corresponds more precisely to the optimal care level. However, the accuracy of this correction cannot be assured in practice. In theory, the justification for this correction relates to the fundamental issue of whether

[460] For example, regulations may require all producers to install two extra devices for a kind of product, which actually is not the case for simple products.

courts or regulators hold perfect information on assessing the due care level, which would open a window for another broad discussion. Traditionally, in the area of production, regulators are empowered to make this decision.[461] Therefore, under mass production, while uncertainties are largely removed due to the burgeoning regulations and standards, the anticipated errors meanwhile exist in individual cases. Therefore, the answer to the first question, whether optimal care level can be precisely determined, is negative under traditional production.

Against this background, we wonder whether the situation is improved in the context of 3D printing. The brief answer to this question might be "no", and it is probably even worse. With 3D printing, not only can errors be made in establishing the optimal care level, but uncertainties also exist to a large extent. As 3D printing is increasingly adopted in a broad range of sectors, there is a pressing need for authorities to set up regulations and standards to determine the due precaution with which a producer should comply in the 3D printing process. In practice, regulatory movements have been observed in some highly demanded areas. For example, in the US, the growing customised medical devices field has posed threats to quality assurance and come to the attention of the FDA (the US Food and Drug Administration).[462] After discussion, specific guidance on 3D-printed food and medical devices was finally issued in December 2017.[463] This 31-page guidance covers safety requirements in all the processes of 3D printing, including the design process, material controls, manufacturing, and post-manufacturing activities. Although this guidance is in nature a non-binding recommendation, it provides producers that employ 3D printing methods with a regulatory expectation.

Almost at the same time, the EU started establishing its new regulatory framework, the Medical Device Regulation (MDR), to reflect the development of customised medical devices.[464] Unlike

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[461] This proposition is also reflected in the EPLD. According to Article 7(d), if "the defect is due to compliance of the product with mandatory regulations issued by the public authorities", then it can be used as a defence for injurers to escape product liability.

[462] Morrison, R. J., Kashlan, K. N., Flanangan, C. L., Wright, J. K., Green, G. E., Hollister, S. J., & Weatherwax, K. J. (2015). Regulatory considerations in the design and manufacturing of implantable 3D-printed medical devices. Clinical and translational science, 8(5), 594-600.

[463] FDA. "Technical Considerations for Additive Manufactured Medical Devices: Guidance for Industry and Food and Drug Administration Staff." 2017. Available at: https://www.fda.gov/media/97633/download.

[464] See Regulation (EU) 2017/745 of the European Parliament and of the Council of 5 April 2017 on medical devices, amending Directive 2001/83/EC, Regulation (EC) No 178/2002 and Regulation (EC) No 1223/2009 and repealing Council Directives 90/385/EEC and 93/42/EEC. OJ L 117, 5.5.2017, p. 1–175.

the guidance issued by the FDA, which is non-binding to producers, the MDR is a mandatory regulation, and it applies to all parties across the EU Member States. It should be noted that to engage in producing customised medical devices, several stringent requirements must be met:

- Only the authorised qualified professionals can prescribe customised devices
- A company cannot make customised devices unless a specific *person responsible for regulatory compliance* is appointed
- All documents must be archived for ten years (15 years for implantable devices)

Similar changes in the sector of drugs and medical devices have also been witnessed in China and Canada, as well as other jurisdictions. With the application of these standards, it is safe to say that the uncertainties in finding negligence have been diminished to some extent.

However, the regulatory framework for 3D printing only exists in a few areas at the current stage. For a wide range of other areas, such as consumer products, concrete regulatory frameworks are still absent. Against this background, the work of finding negligence is left to the *court*, which not only has to find the true care level taken by the injurer but also has to determine the due care level at optimality. In doing so, the court may make two kinds of fault. Firstly, the court may be biased by the experience of mass production and wrongly choose the care level that is respected by mass producers in a related business as the due care level. This approach, on the one hand, may be too stringent to the parties due to the introduction of industrial standards; on the other hand, it may omit some key characteristics in the context of 3D printing. As a result, parties engaging in 3D printing activities may either take excessive precautions in some individual cases or take a lower level of care in some others.[465] Secondly, the court may wrongly apply the standard of a complex 3D-printed product to a simple product. These anticipated errors will also incentivise relevant parties to behave inappropriately.

The discussion so far seems to indicate that resting on the rule of negligence in the context of 3D printing might inevitably distort the effect of deterrence. However, we cannot instantly reach the conclusion that strict liability is superior to negligence whenever courts cannot optimally decide

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[465] For theoretical analysis, see Section 7.3.1.

the care level of producers. As indicated previously, in a bilateral accident as consumers can also substantially influence accident cost, a defence of contributory negligence or comparative negligence always comes with strict liability. Under this background, ensuring the incentive of producers not to be distorted is not the only decisive factor of evaluating the efficiency of liability rules, given the presence of court errors. Whether court errors would distort the deterrence effect on consumers should also be seriously considered. From this perspective, the superiority of strict product liability may not be obvious compared with fault-based rules in the context when 3D printing is organised under separation models.

Finding damages in the context of 3D printing

This part further examines the second kind of court errors and its potential influence on the context of 3D printing, explaining the extent to which errors in determining the damages under liability rules can distort the effect on deterrence. Empirical studies have shown that victims are *under-compensated* in product-related cases involving traditional mass production.[466] Confronted with this situation, since part of damage resulted from their misbehaviours will not be internalised, producers are inclined to behave inappropriately. In this sense, adopting a negligence rule seems to be desirable as it will not distort the deterrence effect given the errors in the assessment of losses.[467] However, this proposition may not hold true in the context of 3D printing.

With traditional mass production, constrained by the economies of scale, however strong the producer is, it has to limit the scope of production to some extent. As such, with the knowledge of the potential product risk and past litigation experience, the producer may well anticipate the errors that will be made by the court in assessing the magnitude of losses. As a consequence, the producer will be induced to behave inappropriately.[468] Regarding this, accurately assessing the magnitude of losses ex-post is of great importance in traditional mass production since producers in this context can relatively well perceive the errors made by the courts.

[466] Dewees, Donald N., David Duff, and Michael Trebilcock. EXPLORING THE DOMAIN OF ACCIDENT LAW: TAKING THE FACTS SERIOUSLY. Oxford University Press, at 194.

[467] See Section 7.3.3 of this chapter.

[468] The economic theory behind it has already been discussed in Section 7.3. For literature, see Kaplow and Shavell (1996), supra note 459.

The situation may be totally different in the context of 3D printing. As economies of scale are largely replaced by economies of scope, people can digitally model or physically print a product without any prior knowledge. In this regard, for these parties, the increasing scope of production will simultaneously increase the difficulty of accurately assessing the magnitude of losses ex-ante. Therefore, an improvement in ex-post assessment to determine damages may not be responded to by the parties. Considering the prohibitive administrative costs that are required to decide accurate damages in individual cases, as well as the fact that the effort needed to improve the ex-post assessment may not significantly change the incentives, with 3D printing the inferiority of strict liability may not be as marked as it is with mass production. If the court is able to assess the damages accurately on average in the context of 3D printing, the superiority of negligence over strict liability is minute. Optimal incentives can be almost equally achieved under strict liability and negligence.

To summarise, the answer to whether damages can be precisely decided in the context of 3D printing is twofold. On the one hand, the court indeed may encounter difficulties in assessing the magnitude of losses in individual cases accurately. On the other hand, we reason that, compared with traditional mass production, this inaccurate ex-post assessment may not generate a serious distortion in the effect on deterrence. Since injurers in the context of 3D printing are less capable of accurately estimating the size of losses ex-ante, they are indifferent to the improvement of ex-post assessment, and they will respect the optimal level of care accordingly. This proposition holds at the current stage. In the long run, however, as parties gradually learn from the scale of risks generated by their activities, and as courts become more capable of determining the magnitude of losses, the ex-post assessment turns out to be more decisive. As a result, negligence may gradually show its advantage.

Finding causation in the context of 3D printing

So far, we have reviewed the impact of court errors in finding care level and the magnitude of liability on the behaviour of producers and consumers in the context of 3D printing. In brief, as 3D printing extensively applies to production industries, we firstly show that it is not easy to find negligence accurately and this dilemma not only applies to fault-based rules, but also to strict product liability (which comes with a defence of consumer's negligence). In addition, the superiority of negligence in terms of assessing the magnitude of losses, which is assumed in theory, is not evident in the context of 3D printing. Given these circumstances, there is not an explicit clue on whether strict product liability or fault-based negligence rules would result in a better deterrence effect in the context of 3D printing. This part explores whether the answer would be a little more explicit when the errors of causation are taken into account.

The previous analysis shows that the deterrence effect could be rather different, provided that the producer is subject to different liability rules. Firstly, if the scope of liability could be optimally decided, both strict liability and negligence have a chance to induce the producer to adopt the optimal care level. Secondly, if causation is unrestricted to some extent, strict liability might be superior to the rule of negligence, since this limited deviation will not drive producers to reduce their precautions. In comparison, fault-based negligence rule is more sensitive to unrestricted causation, especially when level of care meanwhile cannot be precisely decided.

Therefore, in a specific scenario, if the court cannot precisely observe the optimal level of care and can hardly find the optimal scope of causation, it seems that strict liability may result in a better effect on deterrence. However, this superiority is not ensured in reality. Firstly, under strict liability, court errors in assessing the optimal care level of consumers would also distort deterrence. This incident takes place, especially when 3D printing is organised in the way of separation models. In addition, while the optimal scope of liability could be hardly assessed in many cases because of the separation of digital modelling and physical fabrication, it might not be a big problem for many other cases. For example, if the consumer only expects to obtain a simple gadget like a hanger for household use, as the digital design is not complex and it can be accomplished by a desktop printer, it might be not difficult to prove the defect from which process results in damages. From this perspective, finding the scope of causation largely rests on the specific scenario. Provided in specific case causation can be assessed precisely, by setting up a relatively higher level of care, parties would still be induced to optimise their precautions.

7.3.6. Summary

This subsection considers the uncertainties and errors made in determining the elements of liability rules.

In general, confronted with various court errors, strict liability might lead to a better effect on deterrence, provided that (1) producer's activities are more substantial but court cannot easily set up the due care level optimally; (2) the scope of causation can hardly be optimised, especially when causation is unrestricted; and (3) damage can be relatively well assessed. However, as analysed in this subsection, these conditions might not be satisfied in concrete scenarios in the context of 3D printing. When production is organised in a way that digital modelling and physical fabrication are accomplished by separate parties, consumers' behaviours become more important than expected. Also, while the determination of causation might be challenging in specific cases, it would not be problematic in other cases when production relates to small and non-complex scale. All the cases aforementioned implies that considering the influence of court errors, strict liability may not promise a better effect on deterrence than fault-based rules in every circumstance.

7.4. Chapter conclusion

Under traditional mass production, applying strict liability to producers is deemed to improve social welfare by providing producers with the incentive to behave appropriately. In the context of 3D printing, when the whole process of production is respectively undertaken by the CAD file designers and physical fabricators who are strangers to each other, Europe is witnessing a divergence on the issue of which type of liability rules should be offered to the involved parties. As analysed in Chapter 6, while some jurisdictions maintain contractual liability or fault-based rules for these parties, several countries extend the application of strict liability. Under strict liability, producers would be incentivised to optimise their activities. Besides, as the party that holds more information, producers would disclose the full cost of the product to consumers via market price. By doing so, the deterrence effect is expected to be better, since producers whose activities are deemed more dangerous would attempt to optimise their activity levels and what is more, consumers could make better choices by assessing the utility gained from the product in a more accurate way. Under this background, the main interest of this chapter is to explore the extent to which the justifications for strict product liability still hold for separation models in 3D printing. Particularly, we want to know whether applying strict liability to CAD file designers and fabricators would generate a better deterrence effect as observed from mass production and indicated by theory. The conclusion drawn in this chapter seems to contradict this imagination. In brief, the analysis implies that, compared with fault-based negligence rules, applying strict liability to CAD file makers and fabricators might not result in a better deterrence effect.

According to traditional law and economics theory, strict liability is considered to have the potential to optimise the *unobservable* activities of producers, who is considered to generate more risk than consumers. In this regard, the control on activity level also makes strict liability superior to the rule of negligence. However, this superiority is not significant in the context of 3D printing. As we found, compared with traditional production and the "one-stop model" under 3D printing, when production is organised in the way of the "separation model", there is no clue the activities of which of the involved parties are dangerous than others. While it is CAD file makers that prepare the technical proxies for the function and performance of the final product, the activities taken by fabricators are also of great importance. In addition, as consumers play an important role in coordinating the whole production, their activities become significantly crucial, so that they should also be provided with an incentive to optimise their activities. Therefore, the complexity of the separation model indicates that it is difficult to identify a suitable party, whose activities should be optimised prior to the activities of others without any doubt. As a result, applying strict liability to CAD file designers and/or fabricators does not seem to result in a better deterrence than fault-based rules.

Another factor used to justify strict product liability is that consumers can precisely perceive the total cost of a product when producers are subject to strict liability. As the market price is equivalent to the full price of the product, the producer will be induced to behave appropriately. However, the information advantage of strict liability may not be obvious under separation models. As digital designers and physical fabricators come from separate modules, and the whole process of production is coordinated by consumers, it is difficult to identify one party who has the best knowledge of the full price of the product. Therefore, even if strict liability applies to either the digital designer or the fabricator, neither of them may be able to set the market price of a product at its full cost. In addition, given that both of CAD file designers and fabricators are subject to strict liability, the consumer may have a chance to perceive the full price of the final product by adding the two market prices respectively given by the CAD file designer and fabricator. However, as analysed, the market price may not be (accurately) shown to the consumers under several business models (e.g. Model A.1, Model A.2 and Model A.3), the consumer may not correctly access the full cost of the final product. It is noted that these business models are also the ones where contracts fail to disclose sufficient information. As a result, while applying strict liability to separation models may promise an improvement on disclosing more risk information to consumers, its effect may not as significant as that under mass production.

The law and economics theory also indicates that the errors made by courts in applying liability rules may distort the behaviour of parties. Traditionally, deterrence effect is less distorted under strict liability, provided that the producer's care level can be hardly assessed and that the scope of liability cannot be optimised. This implication, however, might not be observed under the separation models in 3D printing. As consumers are playing an increasingly important role in the process of production, to ensure they are induced to take optimal care also has a substantial influence on social welfare. In addition, as analysed, there is a large divergence among different business models in terms of their complexity. In some cases, when the damage is caused by a small gadget, proving causation may not be a big challenge for courts. In contrast, in some others regarding complex modelling and printing processes, finding the scope of liability could be rather difficult. These examples indicate that, whenever court errors are considered, strict liability does not necessarily result in a better deterrence effect than fault-based rules in the context of 3D printing. The extent to which one kind of liability rule is better than the other should be tested in practical cases.

To summarise, under mass production, the producer is deemed as the "most suitable party" that can be targeted to reduce the accidents efficiently and has the best information on the full cost of a product. This "most suitable party", however, is ambiguous when production is organised under the "separation" models in the context of 3D printing. As consumers are playing an increasingly important role in the course of production, providing them with an incentive to behave appropriately is also crucial. From this perspective, the application of strict liability may misallocate the incentive to induce parties behave appropriately.

Besides the deterrence, the issue of risk-shifting also has a great impact on the achievement of the socially optimal outcome. Risk-averse parties are not expected to bear the risk in the end, since it would reduce social welfare. Traditionally, producers are considered to have a better capacity to spread risk than consumers. Under strict liability, by adding the expected damage on average into the price of the product, risk is expected to shift from the more risk-averse consumers to less risk-averse producers. Further, producers may shift the risk to insurers through liability insurance.

Having discussed the issue of how applying strict liability may influence the deterrence effect in this chapter, the next chapter will explain why risk-shifting issue would be problematic if CAD file makers and fabricators are subject to strict liability.

Chapter 8. Risk Preference, Risk-shifting and Product Liability in 3D Printing

According to law and economics theory, the efficiency of a liability rule is not only determined by its deterrence effect, but it also rests on the issue of risk-shifting.[469] Given a specific liability, if it is the risk-neutral party rather than the risk-averse party that ultimately bears the risk, then we can expect an increase in social welfare. Therefore, a liability rule should not only allocate the residual liability to the party who can reduce accident at the cheapest cost, but it also should allocate the risk to the "best risk bearer", who has more *capacity* to bear and spread the risk. If the residual risk bearer in one liability rule has already been the party that can take precautions most efficiently as well as the best risk bearer, then we can reason that this kind of liability rule is efficient.

Traditionally, strict product liability is justified not only because it is presumed to have a better deterrence effect to mass producers, whose behaviour would affect accident cost the most, and to provide a way to show the full price to consumers to help them make decisions, but also because it is a way of risk-shifting.[470] In this sense, compared to consumers, traditionally producers are believed to have a better capacity to bear and spread the risk. However, the risk-shifting function of strict liability is by no means immune from criticism. In practice, specific problems generate in cases that producers are willing to shift risk again to insurers via liability insurance. For example, if insurers can hardly predict the scale of expected harm, they would be reluctant to offer the coverage; in case that producers are offered liability insurance, the existence of adverse selection and moral hazard problem may distort their incentive to behave appropriately. As a result, applying strict liability might not lead to an increase of social welfare compared with using the fault-based rules.

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[469] As Shavell articulated, "it should be emphasized that the allocation of risk is in principle just as important a determinant of social welfare as…the reduction of accident losses." Shavell (2009), supra note 212 at 192. See also Shavell, supra note 2, at 257.

[470] See Ordover (1979) supra note 393.

This chapter proceeds as follows. Firstly, in Section 8.1, the extent to which tort liability rules can take the role of risk-shifting is clarified. By allocating residual liability to the less risk-averse producers rather than to the more risk-averse consumers, strict liability indeed implies a better effect on risk-shifting than negligence. However, the initial risk allocation by strict liability is not the end of risk-shifting. Section 8.2 continues to delve into the case where producers demand risk-shifting via liability insurance. Analysis in this section shows that problems arising from insurability may frustrate producers to further shift the risk, and the existence of adverse selection and moral hazard problem after being granted the insurance may distort their incentive to behave optimally. In Section 8.3, the focus shifts to 3D printing. On the one hand, since residual risk bearers with 3D printing turn out to be more risk-averse than expected, strict liability *per se* as a way of risk-shifting is not remarkably superior to negligence. On the other hand, following the first finding, uninsurability turns to be a big problem, when these risk-averse parties attempt to shift their risks through liability insurance. Worse still, applying strict liability might distort the activities of producers to some extent.

8.1. Strict liability as a way of risk-shifting

With traditional mass production, consumers are considered to be more risk-averse than producers in the face of product risk.[471] Therefore, if there is a mechanism that enables a shift of risk from consumers to producers, social welfare is expected to increase accordingly. Part II shows that parties may shift risk through contractual relationship.[472] In theory, a mechanism of risk-shifting can also be found in tort liability.

Firstly, the rule of negligence per se cannot take on the role of risk-shifting in the sector of production. If producers are subject to the rule of negligence, it is the consumer that serves as the

[471] This standpoint was reflected in classic cases. For example, in the case Escola v. Coca Cola Bottling Co, Justice Traynor argued that the producer situated in the best position to distribute the product risk, and they had the capacity to afford it. He further explained his argument. "Those who suffer injury from defective products are unprepared to meet its consequences. The cost of an injury and the loss of time or health may be an overwhelming misfortune to the person injured, and a needless one, for the risk of injury can be insured by the manufacturer and distributed among the public as a cost of doing business." See 150 P.2d 436, 441 (Cal. 1944) Later in the case Henningsen v. Bloomfield Motors, the same opinion was repeated by Justice Francis. He reasoned that "[The consumer] has the least individual ability to bear the disastrous consequences [of product risks]." See 161 A.2d 69, 87 (N.J. 1960).

[472] See the discussion in Section 4.2.3.

residual risk bearer. If damage is caused to a consumer, but the producer has already taken due care, the consumer has to bear the risk. Given that they are risk-averse, consumers are motivated to shift the risk to other less risk-averse parties. Given that no other risk-shifting mechanisms are offered, the consumer has to bear the risk in the end. purchase coverage through various schemes, such as commercial first-party insurance. To summarise, the analysis shows that consumers are the ultimate risk bearers when the rule of negligence applies. Therefore, the rule of negligence *per se* does not achieve the goal of risk-shifting. Unless victims are provided with additional risk-shifting methods (e.g. first-party insurance), they as the more risk-averse party have to bear the risk under the rule of negligence.

Secondly, let us discuss whether strict product liability *per se* can achieve the goal of risk-shifting. If producers are subject to strict liability, they serve as the residual risk bearers. As a result, given that the consumer takes the due care level, the expected harm will be completely allocated to the producer. Traditionally, imposing strict liability on producers is deemed to achieve the goal of risk-shifting mainly from two perspectives. On the one hand, with more assets, producers are assumed to be more capable of dealing with the product risk.[473] On the other hand, producers can spread the expected losses over all customers by simply including expected liability in the price of the product.[474] In addition, transaction costs are expected to be reduced by adopting the regime of strict product liability.[475]

Therefore, according to the analysis above, if no other risk-spreading instruments are accessible, strict liability seems to play a better role in risk-shifting than the rule of negligence.

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[473] This is also consistent with the "deep pocket" theory, which indicates that since the enterprises hold more assets to bear the risks on their own efforts, it is better to allocate risk to enterprises rather than to consumers. See the Calabresi (1970), supra note 395; Calabresi, Guido, and Jon T. Hirschoff. "Toward a test for strict liability in torts." The Yale Law Journal 81, no. 6 (1972): 1055-1085.

[474] Being subjected to strict product liability, the producer will allocate the expected damage among all the consumers. In this sense, a large number of consumers are involved in risk-distribution under the regime of strict product liability. See Ewold, Francois. "Insurance and risk." The Foucault effect: Studies in governmentality (1991): 197-210.

[475] If there is no strict liability, it is the victim rather than the producer that serves as the residual risk bearer. In this scenario, risk-averse victims would be incentivized to purchase coverage in advance to shift the risk to insurers. Concurrently, each of them has to conclude the insurance contract separately with the insurer. Substantial transaction costs would be generated in this process. In comparison, the provider of insurance (either the producer as a self-insurer or the professional insurer) only needs to conclude the insurance contract via including the premium into the market price, which implies a lower transaction cost in contrast with the case mentioned above. See Priest, George L. "The current insurance crisis and modern tort law." Yale Lj 96 (1987a): 1521.

However, using strict liability to shift product risk could be problematic in reality. Firstly, it may cause an income distribution problem among consumers and it may distort the deterrence to consumers when consumers play an important role in reducing accidents. In addition, if both producers and consumers have a chance to spread the losses via insurances, more problems could generate in the course of seeking liability insurance by producers. Such problems, on the one hand, may frustrate producer to shift risk via liability insurance; on the other hand, they may distort the incentive of behaving appropriately offered to producers. Under this background, the main interest of the following sections is to explain the extent to which risk-shifting through strict liability could diminish social welfare in the context of 3D printing.

8.2. Strict liability perceived as mandatory coverage for consumers

8.2.1. The distributional and deterrence problems

As analysed, strict liability offers an approach to shifting risk from the more risk-averse consumers to the less risk-averse producers. Within this mechanism, whenever a consumer purchases a product, s/he meanwhile purchases coverage in advance. If a person is very cautious and just uses the product occasionally, then s/he expects to spend little money on the coverage of insurance. In contrast, if a person is incautious or uses the product frequently or excessively,[476] higher coverage is expected to be purchased by him/her regarding the level of risk. Therefore, ideally, the expected harm included into the market price should be exactly customised for each consumer. However, in reality, to evaluate the expected harm caused by each consumer might incur prohibitive transaction cost. As a result, for a particular product, the producer can only determine expected harm according to the *average* risk of consumers.[477] By asking for expected harm on average, while it helps shift risk from consumers to producers, it meanwhile might lead to distributive and deterrence problems.

[476] For instance, the consumer places the product in a public area. Since a great number of people have access to the product and it will be used frequently by people, a greater risk will be posed on this occasion compared to the situation where the product is purchased simply for personal use.

[477] See Priest (1987a), supra note 475.

Under strict liability, the consumer who has lower expected harm has to pay an additional premium that is higher than what s/he would have purchased voluntarily. In contrast, for the person who generates a risk that is higher than the average level, s/he would be only asked a smaller coverage than s/he should have been committed to.[478] In this sense, consumers with a lower level of risk are paying premiums for consumers with higher risks.[479] An adverse distributional effect would be observed when the consumers at a lower risk level are also less well-off, since this means that the poor are paying for the risk that is generated by the rich.[480]

In addition to causing adverse distributional effect, the deterrence effect on consumers might also be distorted. Whenever the amount of accident cost also rests on the behaviour of consumers, providing consumers with the incentive to behave appropriately is critical. As the consumer has already been insured through strict product liability, the extent to which s/he will still be incentivised to take optimal care depends on whether his/her behaviour can be observed by the party that finally undertakes the risk (i.e., the producer). Since producers can only assess the premium on average, the consumers whose expected harm is above this level may expect that some accident costs caused by them would not be internalised by themselves. As a result, they are induced to take a lower level of care and to exceed their activity levels.[481]

To summarise the above economic analysis, while strict product liability promises to shift risk from consumers to producers, it may frustrate consumers to some extent. Consumers with a lower level of risk are asked for a higher premium than what they otherwise should have required. As a result, distributional issues as well as deterrence problems are observed by using strict product liability to achieve the goal of risk-shifting.

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[478] See Priest (1992), supra note 206, at 243.

[479] See Priest (1987a), supra note 475; See Priest (1992), supra note 206; See also Winter, Ralph A. "The liability insurance market." Journal of Economic Perspectives 5, no. 3 (1991): 115-136, at 122.

[480] Harrington, Scott E., and Patricia M. Danzon. "Price cutting in liability insurance markets." Journal of Business (1994): 511-538; See also See Faure (2017), supra note 240, at 647.

[481] Shavell, S. (1979). On Moral Hazard and Insurance. The Quarterly Journal of Economics, 93(4), 541-562.

8.2.2. Strict liability as a way of risk-shifting: an analysis in the context of 3D printing

As aforementioned, under traditional manufacturing, since consumers are offered a standard product, risk-shifting could be problematic if consumers are heterogeneous. With the application of 3D printing, the adverse effect regarding distributive issues and deterrence to consumers might be improved. There are two possibilities. On the one hand, the distributive issues and distorted deterrence still exist in some business models. For example, if a consumer chooses to obtain a CAD file from an open-source community (i.e. through Model A.1) or from an online market place (i.e. through Model A.2), as the CAD file is still standardised, the distributive and deterrence problem will still persist. On the other hand, in the scenarios where 3D printing is organised in a customised way (e.g. under Model A.3) or in various service contexts (Model B), the relevant CAD file designer and fabricator may be able to evaluate the expected harm case by case. As the risk-pool is narrowed on a customised basis, the distributional problem and the distorted incentive for consumers are expected to be reduced in these cases.

However, it should be noted that even in the cases where distributional problems and distorted deterrence effect are improved, the dispute on risk-shifting is not closed. Instead, it is just the starting point where risk-shifting problems hit 3D printing. As relevant actors who run a business in the context of 3D printing are SMEs and individuals, considering their capacities, they have a strong motive to shift liability risk toward other less risk-averse parties. It is clarified in the next two sections that risk-shifting emerge before and after the provision of liability insurance to CAD file makers and fabricators.

8.3. Uninsurability in the context of 3D printing

Under strict product liability, producers are at the risk of being sued by consumers, provided that damage were caused by their defective products. Suppose that a producer has sufficient assets to deal with the risk, they may have no preference between paying consumers after lawsuits and shifting the risk in advance. In this sense, this producer is akin to a risk-neutral party and it may not purchase liability insurance from an insurer. However, the assumption that producers show a less risk-averse attitude than consumers does not necessarily mean that they are exactly risk-neutral in reality. Conditioned by their limited capacities in terms of compensation, many producers may also seek to shift their risks through liability insurance to insurers.[482] This is also consistent with the situation in the context of 3D printing, where SMEs and ordinary individuals grow up to take part in production activities.

Seeking for liability insurance may distort social welfare to some extent. On the one hand, in reality, liability risk might be unpredictable to insurers, which may make them reluctant to offer coverage. If this is the case, producers may not be able to shift their risk, which leads them to be exposed to risk and thereby to take a higher level of precaution.[483] On the other hand, after being granted the coverage through liability insurance, they may behave inappropriately.

The analysis in this section will focus on the issue of uninsurability. Further, in the next section, the extent to which liability insurance distorts the deterrence effect on producers is discussed.

After receiving the invitation for offering liability insurance, the insurer may choose to either accept or decline the demand from the producer. The determinant here is the predictability of the risk.[484] Provided that an insurer can precisely evaluate the probability of the accident as well as the magnitude of the damage, the requirement of liability insurance would always be welcomed by the insurer.[485] However, the intention to offer full coverage will decrease with the increasing difficulties in correctly predicting the size of the expected damage. In general, a specific product risk turns out to be uninsurable due to several factors. The following analysis reveals what these factors are and the extent to which they reduce the predictability of risk in the context of 3D printing.

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[482] Mayers, David, and Clifford W. Smith Jr. "On the Corporate Demand for Insurance." The Journal of Business 55, no. 2 (1982): 281-296, at 281-283. It shows that even large companies, which have a greater capacity for self-insuring themselves, in practice, are in favour of shifting their risks through liability insurance.

[483] Shavell, Steven. "On liability and insurance." The Bell Journal of Economics (1982): 120-132; see also Shavell (2009), supra note 401, at 208-210.

[484] The predictability is also the point where the insurance scheme is distinguished from a lottery or bet. See Ewold, Francois. "Insurance and risk." The Foucault effect: Studies in governmentality (1991): 197-210, at 201.

[485] Faure, Michael G., and Ton Hartlief. "Remedies for expanding liability." Oxford Journal of Legal Studies 18, no. 4 (1998): 681-706.

8.3.1. Legal uncertainties in the context of 3D printing

Sources of legal uncertainties

An essential source of unpredictability lies in uncertainty in legal texts, the errors made by courts and the presence of retroactive liability.[486]

The extent to which a producer is subject to strict product liability depends on the scope of product liability in the jurisdiction. While harmonisation has been seen recently across Europe and different Member States have reached consensus on many issues, there is still a significant difference in respect to the scope of product liability between jurisdictions. It should be noted that as long as the relevant legal rules are clear in particular domestic laws and it is clear to which countries a specific product will be distributed, the divergence in the scope of product liability does not generate legal uncertainties. In these circumstances, the size of risk pertaining to these specific products is still predictable to insurers. However, *this certainty would be undermined if the scope of product liability is controversial within one jurisdiction, or it is not clear where the product will be distributed*. As new technologies are widely used in production, uncertainties in the scope of product liability and the destinations of the "product" are important.

The second source of legal uncertainty that will influence the predictability of insurers stems from the errors randomly or systematically made by courts. According to law and economics literature, liability insurance is demanded by injurers under strict liability.[487] In practice, given that courts err in assessing the essential elements of liability rules, risk-averse injurers are also incentivised to purchase liability insurance under the rule of negligence.[488] According to the analysis in Section 7.3, in some cases, injurers run the risk of bearing more risk than they expect. For instance, in the

[486] See Winter (1991), supra note 479.

[487] See Shavell (1982), supra note 483.

[488] See Fagart, Marie-Cécile, and Claude Fluet. "Liability insurance under the negligence rule." The RAND Journal of Economics 40, no. 3 (2009): 486-508. While traditional law and economics literature relaxes the assumption of perfect information held by the court, the injurers are still assumed risk-neutral at the same time. Therefore, seldom discussion has been placed toward the demand for liability insurance under the rule of negligence. See Craswell and Calfee (1986), supra note 425. See also Edlin, Aaron S. "Efficient standards of due care: should courts find more parties negligent under comparative negligence?." International Review of Law and Economics 14, no. 1 (1994): 21-34.

case where the court decides causation incorrectly or in the case where the court overestimates the damage, the predictability of risk would be reduced.

Another factor that makes risk unpredictable is the presence of *retroactive liability*. The liability becomes retroactive when the policy and legal regime on which insurers rely to estimate the premium is changed in the life of the insurance contract or the new rules could apply retrospectively to old risk.[489] By holding a party liable in a retroactive manner, it has to bear the liability risk, even if the act was not considered wrongful at the time of concluding the insurance contract. Retroactive liability is disastrous for insurers because not only do they have to take on the risks that were considered at the date of concluding the insurance contract, but they also have to bear future risks that were not considered at the time.[490] In this regard, although retroactive liability is considered helpful for compensation, its application should be strictly restrained.[491] In the context of 3D printing, if this limitation is clearly maintained in the forthcoming cases and laws and if courts can precisely determine the extent to which a specific risk is subject to which law, retroactive liability should not be a major problem for insurers in terms of diminishing the predictability of risk. If the application of retroactive liability is excessive, which means that the goal of compensation is achieved at the expense of tremendous welfare loss, alternative compensation schemes should be applied.[492]

Legal uncertainties in the context of 3D printing

As analysed in Chapter 7, the current legal framework, either at the EU or the domestic level, does not provide insurers with a clear clue on the liability that is probably borne by relevant parties. On the one hand, it is ambiguous the extent to which CAD file designers and fabricators are subject to strict liability in specific jurisdictions. For instance, in Germany, courts have quite different attitudes on the liability relating to non-embedded intangibles. On the other hand, legal

[489] See Faure and Hartlief (1998), supra note 485, at 687-690.

[490] Faure, Michael, and Paul Fenn. "Retroactive liability and the insurability of long-tail risks." International Review of Law and Economics 19, no. 4 (1999): 487-500.

[491] See Faure and Hartlief (1998), supra note 485, at 689.

[492] See Faure and Fenn (1999), supra note 490.

uncertainties arise as insurers may not be able to estimate the premium, as one production process might be accomplished by actors from multiple jurisdictions. As a result, the insurer may not offer complete coverage to CAD file makers and fabricators when they are subject to strict liability.

Apart from the uncertainties in deciding the scope of liability, uncertainties also exist in the process of applying a specific liability rule once decided.[493] In legal theory, in order to have a party subjected to liability, specific requirements must be satisfied. The previous discussion has already revealed the extent to which legal uncertainties that are encountered by the court in deciding the cases could distort the deterrence effect of relevant parties. The main interest in this part, in contrast, is to check on their influence on risk-shifting efficiency. It is shown that causal uncertainties would have a significant impact on risk-shifting in the context of 3D printing.

Causal uncertainties are actually not new phenomena. Instead, they are widely observed in traditional mass production. As long as the knowledge of the courts lags behind the development of production and the necessary private information is not disclosed to judges, in the case that multiple parties engage in risky activities, there is a possibility that damage turns out to be wrongly linked with the party whose behaviour had nothing to do with the damage at all. Traditionally, whenever the court cannot decide which exact party caused the damage and to what extent, a joint and several liability mechanism may be applied to enable the victim to recover the loss from any party in the supply chain at any amount.[494] Compared to non-joint liability, joint and several liability has been shown to result in a better outcome in terms not only of deterrence but also of compensation for the victim.[495] However, this optimal outcome is determined by two critical conditions. Firstly, it is assumed that every party that engages in risky activity can be identified and will not escape the liability in proportion to its activity. Secondly, it is assumed that every party is solvent, which means that it can afford the losses it causes. Taking these additional factors into consideration, the adoption of joint and several liability is not welcomed by insurance

[493] See Winter (1991), supra note 479, at 123.

[494] Kornhauser, Lewis A., and Richard L. Revesz. “Joint and several liability.” In Boudewijn Bouckaert and Gerrit de Geest, (eds.) ENCYCLOPEDIA OF LAW AND ECONOMICS. VOLUME II. CIVIL LAW AND ECONOMICS. Edward Elgar Publishing Limited, 2000, 625-643, at 626.

[495] Landes, William M., and Richard A. Posner. “Joint and multiple tortfeasors: An economic analysis.” The Journal of Legal Studies 9, no. 3 (1980): 517-555; Kornhauser, Lewis A., and Richard L. Revesz. “Sharing damages among multiple tortfeasors.” The Yale Law Journal 98, no. 5 (1989): 831-884.

companies, especially in the circumstances where insured parties are dispersed or are hard to identify. In these circumstances, insurers run the risk of bearing the risk that was actually caused by the non-insured parties. Such risks cannot be predictable at the time of concluding the insurance contract. As a result, the existence of causal uncertainties and the regime to correct this problem de facto increases the size of the risk that the insurer has to bear.

With traditional mass production, the impact of causal uncertainties on risk-shifting is reduced in several ways. Firstly, ample regulations for traditional manufacturing have been put in place in recent decades. This regulatory regime ensures that sufficient information is made available for judges in precisely deciding causal inference. Secondly, even if the causal inference cannot be correctly decided in court and one party is required to bear all the risks under the solidary liability regime, due to the existence of the contractual relationship, the party bearing the risk can distribute the loss among other parties along the supply chain.

In contrast to traditional mass production, insurers are exposed to a greater risk of causal uncertainties in the context of 3D printing. Firstly, it is more difficult for courts to decide which specific party caused the damage. With 3D printing, a final product could be based on the contributions of tens or hundreds of people. As their particular actions and obligations are not explicitly written into the contract, their contributions are usually difficult to observe. This is especially the case under an open-source environment like Model A.1. In addition, without a contractual relationship, it is extremely hard for the party which is said to bear all the liabilities under solidary liability to obtain reimbursement for the losses from peers. In this case, on the one hand, identifying the identity of the culprit out of all the contributors could be overly difficult. On the other hand, even if it is possible to pinpoint the real injurer, the cost of finding the real injurer might be exceedingly high, because parties are located in different corners of the world.

8.3.2. Uncontrollable adverse selection and moral hazards

If insurers hold perfect information, the insured parties will be incentivised to optimise their level of care and level of activities.[496] In other words, insurers are not only able to determine precisely

[496] See Shavell (1982), supra note 483; Wagner, Gerhard. "Tort law and liability insurance." In Michael Faure (ed.) ENCYCLOPEDIA OF LAW AND ECONOMICS VOL I TORT LAW AND ECONOMICS. Edward Elgar Publishing Limited. 2009,

the size of risk at the time of concluding the insurance contract, but they can also identify any inappropriate behaviours taken by the insured parties afterwards. However, complete information may not be guaranteed in reality since such private information is held by the insured party and insurers may have to make a colossal effort to observe it.[497] If part of the risk is not reflected in the premium or if insurers fail to supervise insured parties after concluding the contract, insured parties will be induced to reduce their level of care and to undertake excessive activities.[498]

Adverse selection and moral hazard in a nutshell

Adverse selection takes place when insurers have difficulty in precisely estimating the risk of each specific party ex-ante.[499] In this situation, since the insurer can only determine the premium at the average level, producers with a lower risk level have to pay a higher premium. Instead of purchasing liability insurance from the insurance company, these producers are motivated to shift to self-insurance. What is worse, the increasing exposure to tort liability would lead many producers to reduce their activities. In this sense, not only are products withdrawn from the market, but their research and plans for new products would also be put aside.[500] As the low-risk producers are driven out of the liability insurance market, the risk pool will be full of producers with higher risk. As a result, insurers are de facto bearing more risk than expected, and some coverage would be withdrawn by them from the market.[501] This reasoning is by no means a hypothesis; the

377-405, at 386-388; see also See Akerlof (1970), supra note 266; Faure, Michael G, and Ton Hartlief. "Insurance and expanding systemic risks." OECD (2003), at 109.

[497] See Wagner (2009), supra note 496, at 390.

[498] See Shavell (1982), supra note 483.

[499] See Akerlof (1970), supra note 266; Rothschild, Michael, and Joseph Stiglitz. "Equilibrium in Competitive Insurance Markets: An Essay on the Economics of Imperfect Information." The Quarterly Journal of Economics 90, no. 4 (1976): 629-649; see also Winter (1991), supra note 479, at 122.

[500] According to data, these phenomena were widely observed after strict product liability was established in the US. A survey conducted in 1986 reported that 47 percent of respondents had withdrawn products, 39 percent had decided to suspend the introduction of new products, and 25 percent had decided to discontinue the R&D of new products. See Priest, George L. "The modern expansion of tort liability: its sources, its effects, and its reform." Journal of Economic Perspectives 5, no. 3 (1991): 31-50.

[501] See Priest, George L. "Modern tort law and its reform." Val. UL Rev. 22 (1987): 1, at 2.

literature shows how an increasing adverse selection problem, which was linked to the expansion of tort liability, caused the crisis in the commercial insurance market in the 1970s.[502]

The uncontrollable moral hazard problem could also create difficulty for insurers in accurately predicting the size of risk. *Moral hazard* usually occurs in a situation where insurers find it hard to monitor the activities of the insured parties after offering coverage.[503] In this case, as risks in the future have already been shifted to the insurer, the insured party might be less inclined to behave appropriately. As a result, the insured party is motivated to take fewer precautions and to undertake excessive activities.[504] In order to avoid moral hazards, the insurer has to take measures to ensure that the insured parties take optimal precautions. However, this could be difficult to achieve in reality since an insurer has to supervise the insured at all times, the cost of which would be extremely high.

To summarise, if insurers hold perfect information, which means that neither adverse selection nor moral hazard is presented to insurers, the first-best outcome would be achieved. In contrast, if insurers cannot differentiate risk at the time of concluding an insurance contract, or they cannot effectively supervise insured parties after concluding the contract, they would be exposed to more bad risks than good ones. Even if providing coverage still generated a second-best outcome in this situation, if these problems become uncontrollable to insurers, they would be incentivised to withdraw the coverage from insured parties. In reality, while particular well-recognised risksare uninsurable[505], most of the risks are not entirely insurable despite the severity of adverse selection and moral hazard problems. Uninsurability thus means that a specific risk cannot be insured at its

[502] Danzon, Patricia M. "Tort reform and the role of government in private insurance markets." The Journal of Legal Studies 13, no. 3 (1984): 517-549; Clarke, Richard N., Frederick Warren-Boulton, David D. Smith, and Marilyn J. Simon. "Sources of the crisis in liability insurance: An economic analysis." Yale J. on Reg. 5 (1988): 367; Trebilcock, Michael J. "The role of insurance considerations in the choice of efficient civil liability rules." JL Econ. & Org. 4 (1988): 243; Priest (1991), supra note 500, at 42-47.

[503] Arrow, Kenneth J. "Uncertainty and the Welfare Economics of Medical Care." The American Economic Review 53, no. 5 (1963): 941-73; Baker, Tom. "On the genealogy of moral hazard." Tex. L. Rev. 75 (1996): 237.

[504] See the discussion under 3.3. For original analysis, see Arrow, Kenneth J. "The economics of moral hazard: further comment." The American Economic Review 58, no. 3 (1968): 537-539; Pauly, Mark V. "The economics of moral hazard: comment." American economic review 58, no. 3 (1968): 531-537. Shavell (1979), supra note 481.

[505] For example, criminal sanctions and catastrophic disasters (e.g. earthquakes and floods). See Jaffee, Dwight M., and Thomas Russell. "Catastrophe insurance, capital markets, and uninsurable risks." Journal of Risk and Insurance (1997): 205-230.

full coverage. In practice, measures like excesses make a specific risk insurable in general, albeit at the expense of sacrificing a portion of the coverage.[506]

Uncontrollable adverse selection and morals hazard in the context of 3D Printing

In theory, if the parties with high risk are in the same risk pool as those with lower risk, insurers would face an adverse selection problem. The way to alleviate this problem is to narrow the risk pool as much as possible to ensure that people with a similar level of risk are included in the same group. However, due to the limited ability of insurers and the prohibitive cost of risk-differentiation, adverse selection can be hard to eliminate. The problem of risk-differentiation persists with 3D printing, and it could be even worse than with traditional mass production.

Within traditional production, while the economy of scale serves as a barrier for producers to enter the market and to expand the scope of production, it also plays a vital role in differentiating producers. In other words, the existence of scale economies constrains a producer from shifting production activities from one sector to another. Therefore, as the scope of production of a specific producer is known to the insurer to some extent, the insurer can assess and compare the expected harm resulted from different parties. Later, the insurer can place the producers with similar risks into the same group. However, risk-differentiation based on scale economies cannot assist the insurer in the context of 3D printing. To illustrate, while the adoption of 3D printing removes the threshold of scale economies to a large extent and makes production accessible to a great variety of members, it also blurs the differentiation of various actors who take part in 3D printing activities. Since extending the scope of production generates little marginal cost with 3D printing, parties can embrace a wide range of products. As a result, a great number of applicants, who engage in a wide range of production activities but have considerable differences in levels of risk, would be grouped into the same risk pool. With such a wide risk pool, we can reasonably imagine that some risk-averse parties would have to pay a much higher premium than they should have. In the end, the adverse selection problem may drive these low-risk policyholders out of the insurance market.

[506] Arlen, Jennifer H. "Compensation systems and efficient deterrence." Md. L. Rev. 52 (1993): 1093; Wagner (2009), supra note 496, at 391-392.

That risk-differentiation is expected to be difficult with 3D printing can also be seen by the fact that few signals can be accessed by the insurer. In the past, insurers accumulated much information and portfolios in support of their decision-making on risk-differentiation. In addition, other signals, such as certification and regulatory compliance, are also accessible to insurers. However, all these materials are less visible with 3D printing.

In addition to the difficulty of risk-differentiation, *monitoring* CAD file designers and fabricators could be also problematic in the context of 3D printing. Compared to supervising mass producers, it will be extremely difficult for insurers to check on the activities undertaken by each individual producer in the context of 3D printing. Theoretically, the insurer may make every effort to supervise individual producers at all times. In an extreme case, the insurer can install a camera in an insured's room and employ thousands of people to inspect the behaviour of the insured all the time. However, this can never happen in reality due to the prohibitive expense as well as invasion of the fundamental rights of the insured (e.g. privacy).

Increasing the predictability of risk in the context of 3D printing

Two methods are available to overcome the unpredictability of risk in the context of 3D printing. Firstly, insurers can invest in narrowing the risk pools to make sure that bad risks can be distinguished from good risks. Secondly, insurers may develop the schemes that can provide insured parties with extra incentives to increase their level of care.

In order to differentiate risks as narrowly as possible, in the course of underwriting, insurers have to collect enough information to distinguish the potential risks generated by the insured.[507] By doing so, insurers can analyse each party's propensity to engage in risky activities and accurately categorise them into different groups.[508] Similar to a conventional insurance contract, insurers can always ask CAD file makers and fabricators to answer some general questions, such as whether they have incurred any liability for their designs or products and whether there have been

[507] Ben-Shahar, Omri, and Kyle D. Logue. "Outsourcing regulation: how insurance reduces moral hazard." Mich. L. Rev. 111 (2012): 197, at 206.

[508] Baker, Tom, Peter Siegelman, and J. Arlen. "The law and economics of liability insurance: a theoretical and empirical review." In Jennifer H. Arlen (ed.) RESEARCH HANDBOOK ON THE ECONOMICS OF TORTS. Edward Elgar Publishing. 2013, at 169-195.

complaints about the failure of their products to function.[509] However, it should be noted that such information is not enough to distinguish the risk of individual producers in the context of 3D printing.[510] In this regard, while risk-differentiation can be based on the answers to general questions, this is a very poor way of distinguishing risks. Therefore, information specific to 3D printing should be required by insurers before an insurance contract is concluded. In practice, insurers can always ask the insured to report background information. Such information includes the method of 3D printing, the education background of the insured parties, the function and the potential use of the CAD file or final product, the scale of distribution, etc.[511] However, while collecting personal and background information from individual producers can help insurers to differentiate the risks of various parties, it increases the cost of risk-differentiation as well.

In practice, several measures are developed to control moral hazard at a mild range. Presuming that the insured will be incentivised to take fewer precautions as long as they are offered coverage, insurers may decide only to provide partial coverage.[512] The essence of partial coverage is aimed at increasing the care level of the insured by posing partial risks to them. Partial coverage is reflected in multiple forms within the clause of insurance contracts. A direct way is to embed a clause in the insurance contract on the limit of coverage. For example, insurers can include in the contract the particular circumstances in which risks cannot be insured.[513] Partial coverage can also be accomplished by bundling defence coverage with indemnity coverage. By doing so, insured parties have to pay for the costs of settlements and judgements.[514] Moreover, methods such as

[509] Robinson, Chris, and Bingyong Zheng. "Moral hazard, insurance claims, and repeated insurance contracts." *Canadian Journal of Economics* 43, no. 3 (2010): 967-993.

[510] In the context of 3D printing, it is quite common at the current stage that the insured is a new entrant of the market. Therefore, no record is available to insurers to assess the risks borne by such parties. See Swiss Re. "3D Printing: From Hype to Reality and Insurance Implications." 2017. Available at: https://www.casact.org/education/rpm/2017/presentations/CL-1.pdf. Visited on September 16th, 2018.

[511] Underwriting challenges have been taken into account by some insurance companies. For example, a study from Swiss Re suggested that "underwriters need to follow the technology and ask more questions". See Swiss Re. id.

[512] See Abraham, Kenneth S. "The Costs of Attitudes." *Yale.L.J.* 95 (1986): 1043. See also Baker, Tom. "Liability insurance, moral luck, and auto accidents." *Theoretical Inquiries in Law* 9, no. 1 (2008): 165-184.

[513] For example, insurers can design the insurance contract in a way that the losses, which pose a high level of moral hazard, the coverage will be excluded or reduced accordingly. See Faure and Hartlief (1998), supra note 485. See also See Baker et al. (2013), supra note 508. In addition, contracting into exclusions is also observed in certain types of activities and correlated risks (e.g. flood and earthquake). See Ben-Shahar and Logue (2012), supra note 507, at 215.

[514] See Baker et al. (2013), supra note 508.

excesses, coinsurance and caps also lead the insured to bear partial risks. Within these mechanisms, insurers will pay the compensation only if a specific scale of damage is triggered.[515]

In actual, besides the conventional measures to deal with adverse selection and moral hazard problems, new measures are underway. As will discussed in Part IV, platform as the party that has a better position to observe the behaviour of relevant actors might offer more complementary measures to help insurers to reduce information asymmetry.

8.3.3. Summary

This subsection focuses on the issue of the accessibility of liability insurance, the purpose of which is to illustrate the factors that can potentially preclude insurers from offering the coverage. In the context of 3D printing, risk could be less predictable than with traditional mass production and thus less insurable in several conditions, ranging from uncertainties in the legal system to a lack of information on the behaviour of insured parties. In these situations, insurers may have to bear more risk than expected, which leads them to provide reduced coverage. Therefore, the socially optimal outcome is not achieved where liability insurance is not available to CAD file makers and fabricators. In theory, uninsurability problem might result in an outcome that is even worse than the situation where liability insurance is offered with mild adverse selection and moral hazard problems.[516] In the next section, the discussion moves to the scenario where liability insurance can

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[515] While these mechanisms all remain partial risks to insureds, they perform differently. Deductibles refer to the fixed amount borne by insureds. Coinsurance instead is a fixed percentage that should be borne by insureds. In comparison, caps refer to the largest amount that can be claimed by insureds. These three mechanisms are adopted under different scenarios. In general, deductibles apply to the cases with small losses; co-insurance applies to the cases with medium losses; caps apply the cases with huge losses. See Avraham, Ronen. "The Economics of Insurance Law-A Primer." Conn. Ins. LJ 19 (2012): 29.

For a general overview of such mechanisms, see Priest (1987a), supra note **Error! Bookmark not defined.**, at 1571-1576. See also Schwartz, Alan. "Proposals for products liability reform: A theoretical synthesis." *Yale. L.J.* 97 (1987): 353, at 405. For the disadvantages of deductibles, see Cohen, Alma. "The disadvantages of aggregate deductibles." *Topics in Economic Analysis & Policy* 6, no. 1 (2006). Two prominent merits are observed in literature by applying deductibles and coinsurance. Firstly, by offering insurance policy conditions with deductibles, insureds are incentivized to be sorted into different groups on their own. This is firstly found by Rothschild and Stigliz. See Rothschild, Michael, and Joseph Stiglitz. "Equilibrium in Competitive Insurance Markets: An Essay on the Economics of Imperfect Information." The *Quarterly Journal of Economics* 90, no. 4 (1976): 629-49. Secondly, insureds may decide to take optimal precaution on their own interest, even if it is not observable to insurers. See Avraham (2012).

[516] Shavell (2004), supra note 2, at 261-264; see also Shavell (2009), supra note 212, at 213.

be accessible to CAD file makers and fabricators, the aim of which is to examine the extent to which the provision of liability insurance distorts social welfare.

8.4. The impact of liability insurance on deterrence in the context of 3D printing

In this section, the case where insurance is accessible to risk-bearing parties is considered. The main interest is to explain how offering liability insurance could distort deterrence in the context of 3D printing.

8.4.1. Liability insurance: taking adverse selection and moral hazards into consideration

Whenever producers are provided with liability insurance, law and economics literature concludes that the effect on deterrence is largely determined by the information held by insurers.[517] In particular, if insurers hold complete information, which means that they can precisely differentiate risks between various insured parties and they can monitor their behaviours sufficiently, the insured parties (i.e., the injurers) would be incentivised to optimise their behaviours. In this situation, the socially optimal outcome is achieved, since not only producers are still induced to optimise their behaviours, but also risk-averse parties successfully are able to shift risk in advance.

In contrast, if the information held by insurers is insufficient, insured parties would feel that the cost caused by their activities would not be fully internalised, so they will be incentivised to lower the level of care to some extent. In this circumstance, the desirability of liability insurance is decided after comparing the social welfare respectively resulted by the circumstance where no insurance is offered and the scenario where liability insurance is offered. As for this issue, law and economics theory implies that when moral hazard problem prevents insurers from monitoring insured parties, the distortion of deterrence is *moderate*.[518] In other words, even if the deterrence

[517] Shavell (2009), supra note 212, at 211-212.

[518] Shavell (2009), supra note 212, at 213.

effect might be diluted by providing injurers with insurance, the outcome is still better than the situation where insurance is not available.[519]

However, it must be noted that concluding offering liability insurance is more efficient than not offering that is correct based on a critical assumption, which is that producers are *solvent*. Provided that the producers confront judgment-proof-problem, offering them liability insurance might generate a lower level of social welfare, which is even worse than no coverage is offered at all.

8.4.2. The consideration of the judgment-proof problem

In the context of 3D printing, unlike enterprises that take on liability to the limit of their registered assets, digital designers and fabricators may endure compensation far above their capacity. So far, we have relaxed the assumption to the extent that risk-averse injurers have access to liability insurance to shift risk but not yet to the extent that they may have insufficient assets to compensate victims.

According to law and economics analysis, insolvent parties might have little incentive to take optimal care and they are more induced to take more risky activities.[520] Theory also indicates that the distortion would be more severe under strict liability than under fault-based rules.[521] The existence of the judgment-proof problem also has a great influence on the motivation of parties to purchase insurance. Given insolvency, since the utilities gained by them under partial coverage may be smaller than the ones when they purchase full coverage, the motive of risk-averse parties to purchase full coverage might be diminished.[522] Therefore, the insolvent parties would like to

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[519] However, as we will reveal later in this part, the result could be undesirable provided that the injurers are insolvent in this later situation.

[520] Shavell, Steven. "The judgment proof problem." International Review of Law and Economics 6 (1986) 45-58.

[521] Under negligence rule, since tortfeasors can avoid the entire liability by only taking the optimal care level, they will still retain their care level at optimality. Only in the case that their assets are sufficiently small (even smaller than the costs of optimal care) and in the case that the unrestrictive scope of liability is accurately identified by the court, tortfeasors will lower their optimal care level. However, as retaining optimal care level will only enable tortfeasors to reduce the likelihood of liability under strict liability, they will be induced to take less care level. See Shavell, Steven. "The judgment proof problem." *International Review of Law and Economics* (1986), vol.6: issue 1, 45-58.

[522] See Shavell (1986), supra note 521; Sinn, Hans-Werner. "Kinked utility and the demand for human wealth and liability insurance." European Economic Review 17, no. 2 (1982): 149-162; MacMinn, Richard D., and Li-Ming Han. "Limited liability, corporate value, and the demand for liability insurance." Journal of Risk and Insurance (1990): 581-607.

choose a partial instead of the full coverage. In an extreme case, if the premium (or expected losses) is expected even higher than the asset of the insolvent tortfeasors, they might not consider purchasing liability insurance at all.[523]

To summarise, provided that injurers suffer the judgment-proof problem, they are inclined to purchase limited coverage and the incentive to optimise behaviours would be further exacerbated compared with the case where the injurers are solvent. Therefore, in a circumstance when risk-averse producers are insolvent and their behaviours can be hardly controlled by insurers, shifting risk through liability insurance might be the worst case, which results in even less social welfare than the case that no liability insurance is offered at all.

Compared with mass producers, CAD file makers and fabricators in the context of 3D printing are inclined to suffer insolvent problems. Therefore, providing these actors with liability insurance to help them shift product risk might not be a smart choice, because the social welfare resulted from this situation might be even worse than the situation where no coverage is offered. The analysis in this case also indicates that requiring actors to purchase liability insurance *mandatorily* might not be an appropriate policy to be implemented in the near future. In this regard, although mandatory insurance might ensure a better risk-shifting effect on relevant actors and a higher level of compensation to consumers, its achievement is at the expense of under-deterrence.[524] Mandatory insurance is desirable, only if adverse selection and moral hazards can be well controlled.[525]

8.4.3. Summary

To conclude, the discussion in this section shows that applying strict liability and liability insurance to shift risk might distort the incentive of relevant actors to behave appropriately. In the context of 3D printing, as insurers might confront unsurmountable adverse selection and moral hazard problems, CAD file makers and fabricators might be under-deterred after purchasing the coverage. While this distortion of social welfare might be moderate compared with the scenario

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[523] See Shavell (1986), supra note 521.

[524] Polborn, Mattias K. "Mandatory insurance and the judgment-proof problem." International Review of Law and Economics 18, no. 2 (1998): 141-146.

[525] Faure, Michael G. "Economic criteria for compulsory insurance." The Geneva Papers on Risk and Insurance-Issues and Practice 31, no. 1 (2006): 149-168.

where liability insurance is not offered at all, the outcome could be worse given that many parties might be insolvent to the damage.

8.5. Chapter conclusion

Traditionally, making producers strictly liable is deemed not only as a way of deterrence but also as a method of risk-shifting. Mass producers, which are usually in the form of entities, are less risk-averse to risk. More importantly, they are able to spread the risk over consumers by adding the expected harm into the market price. The discussion in this section, however, indicates that using strict liability to shift risk might not generate an efficient outcome. Firstly, shifting risk through strict liability may generate adverse distributive effect and distort the deterrence effect on consumers, especially when activities are run under Model A.1 and Model A.2. Secondly and more importantly, as CAD file makers and fabricators are more risk-averse than mass producers, they have an increasing demand for liability insurance, which might lead to two problems. On the one hand, uninsurability issue might serve as an obstacle for injurers to obtain liability insurance, in which situation risk-averse actors would remain as uninsured. On the other hand, once insured, the fact that CAD file makers and fabricators are more likely to be insolvent might lead to a heavier distortion on deterrence effect.

In a situation that *both* producers and consumers are able to spread losses via insurance, the discussions in this chapter might direct the debate against the application of strict liability. Compared with strict liability and liability insurance, if fault-based rules are established, while consumers being the more risk-averse party would have to bear the risk in the first place, with the access to first-party insurance they may shift risk in a way without distorting deterrence effect too much. Specifically, in the context of 3D printing, we may expect the superiority of first-party insurance to liability insurance from three perspectives. Firstly, consumers are able to choose the coverage according to their demand, so that parties with low risk do not need to pay for high-risk parties. Secondly, risk turns to be more predictable to insurers, since the amount of insured amount is normally fixed in the contract. Thirdly, adverse selection and moral hazard problems are less problematic for first-party insurance. To summarise, the justification of strict liability from the risk-shifting perspective is diluted in the context of 3D printing.

Conclusions

The analysis in Part II concluded that contracting over product risk might not generate the socially optimal outcome due to the existence of transaction cost and information asymmetry and the difficulty of risk-shifting. This result could be even worse when parties rely on specific business models (e.g. Model A.1, Model A.2 and Model B.2). Conventionally, tort liability is considered as a crucial way to improve social welfare regarding the accidents. Especially, strict product liability is applied to deal with the accidents caused by defective products. The purpose of Part III is to examine whether strict liability is still the appropriate choice as many of the Member States imagined, which generates the optimal level of deterrence and ensures risk-averse parties not to bear risk in the context of 3D printing.

According to the analysis in Part III, either strict liability or fault-based rules are expected to induce relevant parties to take the optimal level of care. This implication endows tort liability with a critical role in reducing accident cost on the basis of contractual relationship. Conventionally, producers are subject to strict liability to the damage caused by the defective product made by them. According to the positive legal analysis, in the context of 3D printing, it is ambiguous whether CAD file makers and fabricators whose business rest on separation models are defined as the “producers” or not. Therefore, the core issue to be discussed when tort liability approaches to 3D printing is whether strict liability should apply to CAD file makers and/or fabricators. According to law and economics analysis, this question must be answered in a way by examining whether a higher level of social welfare could have resulted from the application of strict liability than from the fault-based rules.

Traditionally, producers are subject to strict liability, because they are considered as the “most suitable party”. Applying strict product liability can be justified by the following reasons: (1) providing producers with an incentive to behave appropriately is more important; (2) the full cost of a product can be perceived by consumers through market price with the application of strict liability; and (3) consumers who are deemed as more risk-averse could shift risk to the less risk-averse producers. If these justifications still hold in the context of 3D printing, applying strict liability to CAD file makers and fabricators would still be a imagined as a way to increase social welfare. The analysis in this chapter, however, concludes that such justifications do not hold in the context of 3D printing.

The *main finding* of Part III is that, when production is organised in a way that consumers determine that source of digital modelling and physical fabrication, there is no longer a suitable party as traditional producers. Therefore, applying strict liability may not result in the socially efficient outcome.

Firstly, there is not a party who constantly serves as the "most suitable party" to reduce accidents at the least cost. Under separation models, not only the CAD file makers but also the fabricators have substantial impact on the final performance of a product. More importantly, consumers being the coordinator of the whole production process should be provided with an incentive to behave appropriately. If strict liability applies, then consumers would not be induced to optimise their activities.

Secondly, there is not a party who is best-positioned to perceive and show the full cost of the product. Under separation models, the full cost is determined by two separate parties. Since the CAD file maker and the fabricator are strangers to each other, in a given scenario, it is difficult to decide which party is more capable than the other to assess the full cost. Therefore, imposing strict liability on either of two parties may not ensure this party to disclose the full cost of the final product. If strict product liability applies to the CAD file maker and fabricator separately, the consumer has to add up the full price separately offered by each party. However, this method might not ensure consumers to precisely perceive the full cost. If the CAD file is obtained from an open-source environment (i.e. under Model A.1), no price is offered to help consumers understand the full price of the CAD file.

Thirdly, CAD file makers or fabricators may not be the most suitable party to spread losses in the context of 3D printing. Compared with traditional mass producers, CAD file makers and fabricators in the context of 3D printing seem to be far more risk-averse. In this regard, compared with the situation of having consumers bear risk, having these actors to bear the risk in the first place may not result in an obvious increase in social welfare. What is more, further problems take place when CAD file makers and fabricators seek for liability insurance. As analysed in Chapter 8, relevant parties may encounter uninsurability problems in the course of conclusion contracts with insurers; also, as these parties tend to be more insolvent than mass producers, offering coverage to them may distort the deterrence effect on them. Therefore, in the event that both CAD file makers/fabricators and consumers have access to risk-shifting mechanisms, the problems of liability insurance turn to be a debate against the preference of strict liability.

Having briefly concluded the findings in this part, a general overview of the function of the contractual relationship and tort liability in terms of deterrence and risk-shifting could be preliminarily summarised here. Firstly, the contractual relationship may do a good job for the circumstance where bargaining is intensive (such as under Model A.3, Model B.1 and Model B.3). In these business models, bargaining may lead parties to increase the level of care to the extent that can be observed and concluded into the contract. However, for other circumstances, bargaining over product risk may result in a higher level of social cost than optimality. Secondly, tort liability, either strict liability or fault-based rules would provide all relevant parties with an incentive to take optimal care level. Strict liability is not evident to promise a higher level of social welfare than fault-based rules. It should be noted that the result concluded from the contractual relationship and tort liability is highly dependent upon the information possessed by contractual parties as well as by courts which are responsible for deciding the level of care.

Under this background, the analysis in Part IV would focus on the role of regulators and platform. The main interest if to explore the extent to which these two parties are able to improve the effect deterrence as well as risk-shifting.

PART IV

DETERRENCE AND RISK-SHIFTING IN THE CONTEXT OF 3D PRINTING THROUGH THE LENS OF REGULATION AND PLATFORM GOVERNANCE

Introduction

The application of 3D printing could generate considerable product risks. In order to achieve the socially optimal outcome, specific instruments are expectable to incentivise the parties who contribute to accident costs to optimise their behaviours and to ensure that risk-averse parties do not bear the risk in the end. The discussion so far concludes that when the whole process of production is separately undertaken by CAD file makers and fabricators who come from various business models, the socially optimal outcome is not easily accomplished through either the contractual relation or tort liability. In the contractual relationship, due to the presence of prohibitive transaction costs and information asymmetries, contractual parties may not reach an agreement than can incentivise them to behave optimally. In addition, risk-averse parties may not shift their risk via contracts. Under tort liability, while parties are induced to respect the due care level of care, the deterrence could be distorted because of the errors made by courts and judgment-proof problem suffered by the relevant parties. Under this background, complimentary instruments are necessary to provide relevant parties with an additional incentive to optimise their behaviours and to smooth the process of risk-shifting.

Two instruments are specifically explored in Part IV. In Chapter 9, the core issue to be discussed is the extent to which regulations can intervene in the contractual process so as to induce actors to take sufficient precautions. In Chapter 10, the focus shifts to platform governance to explore how platform can contribute to improving social welfare by incentivising the relevant parties to behave appropriately, and spreading the risk efficiently.

Chapter 9. Regulations as a Complementary Instrument in the Context of 3D Printing

In economic theory, allocating the product risk through contractual relations or tort liability rules is the essence of a market-based system.[526] In this sense, people preserve the value of economic liberty and leave the decision-making to market participants. Given certain key assumptions, these market mechanisms can allocate the product risk efficiently. It has been discussed in the literature that private parties hold an inherent information advantage since they are in a better position to assess the potential risk of their activities. On this basis, liability rules are considered to be superior to regulations, so that the state does not need to intervene in private activities.[527]

However, as analysed previously, the contractual relationship might not incentivise relevant parties to behave appropriately in the context of 3D printing. In practice, the presence of information asymmetry in the course of contracting over product risk may lead CAD file makers and fabricators to behave inappropriately. Under specific business models (e.g. Model A.1, Model A.2 and Model B.2), the deterrence effect could be even more distorted. In this situation, besides using other market-based mechanisms to restore the distorted incentive of contractual parties (e.g. tort liability), regulations may play a role in alleviating this private law failure.[528]

[526] Ogus, Anthony I. REGULATION: LEGAL FORM AND ECONOMIC THEORY. Hart Publishing, 2004, at 15-28.

[527] See Shavell, Steven. "Liability for harm versus regulation of safety." The Journal of Legal Studies 13, no. 2 (1984): 357-374.

[528] See Ogus (2004), supra note 526, at 190; Stapleton, J. (1986). Products Liability Reform-Real or Illusory. Oxford J. Legal Stud., 6, 392; Trebilcock, Michael J. "Incentive issues in the design of no-fault compensation systems." U. Toronto LJ 39 (1989): 19; Viscusi, W. Kip. REFORMING PRODUCTS LIABILITY. Harvard University Press, 1991.

The complementarity between liability and regulation in terms of minimising accident cost is no longer a new idea in the literature.[529] The question asked here is the extent to whuch regulations could resolve the problems that are not solved by private law in the context of 3D printing. In general, regulations might improve deterrence effect in two ways. On the one hand, by setting up standards, regulations may *directly* intervene in the behaviour of relevant parties.[530] On the other hand, by requiring relevant parties to disclose more information that is necessary for assessing the product risk, regulations can help contractual parties to make decisions in a more effective way.[531] This chapter explores the residual role of regulations in terms of deterrence.

9.1 Regulation as a method of deterrence: a precis

In general, various regulations can be divided into three categories: information regulation, mandatory standard and prior agency approval.[532] This subsection explains the relative superiority of each of the regulatory methods in theory.

9.1.1. Information regulation

Information regulation refers to the mechanism that induces the involved parties to disclose safety information actively to consumers.[533] In general, information regulations are divided into two types. The first type is where the parties are required to disclose *specific characteristics* of the product directly and clearly. The second type is where *certificates* inform the parties of the potential risk.

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[529] See Rose-Ackerman, Susan. "Regulation and the Law of Torts." The American economic review 81, no. 2 (1991): 54-58; Burrows, Paul. "Combining regulation and legal liability for the control of external costs." International Review of Law and Economics 19, no. 2 (1999): 227-244.

[530] See Schwartz, Alan, and Louis L. Wilde. "Intervening in markets on the basis of imperfect information: A legal and economic analysis." U. Pa. l. REv. 127 (1978): 630; Beales, Howard, Richard Craswell, and Steven C. Salop. "The efficient regulation of consumer information." The Journal of Law and Economics 24, no. 3 (1981): 491-539.

[531] It is evidenced that if regulators act in the public interest, disclosing information via regulation is better than private disclosure. See Jost, Peter-J. "Disclosure of information and incentives for care." International Review of Law and Economics 15, no. 1 (1995): 65-85.

[532] See Ogus (2004), supra note 526, at 141-244.

[533] See Ogus (2004), supra note 526, at 121.

The elements required by the information regulations range from price to the quantity or quality of the product. For example, regulators may require the involved parties to reveal the composition that is used for the production of experience goods[534] and credence goods.[535] In these circumstances, by adopting this objective criterion, users are able to evaluate and compare the safety of the products. The failure to disclose such information may not prevent a party from engaging in activities in the market, but it may run the risk of bearing the ex-post liability. It is noteworthy that mandatory information disclosure may not always generate a desirable outcome. The Disclosure of information by requiring relevant parties to reveal particular key characters can significantly help overcome the inadequacy of information that is perceived by consumers. However, as consumers may have limited time to make decisions and as they may have insufficient knowledge to assess the relevant information, too much information turns out to be burdensome for the consumers.[536]

Apart from mandatory information disclosure, regulators also establish a system of certification to help consumers distinguish parties. If a party successfully gains a certificate, it is a signal to consumers that its products satisfy particular *voluntary* standards.[537]

9.1.2. Prior approval

Prior approval means that a party cannot engage in specific activities unless it successfully obtains a permit from a regulatory agency.[538] Unlike information regulations (e.g. certificates), in which parties that fail to comply with specific standards can still run a business in the market, the

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[534] "Experience goods" refer to the goods whose safety can be assessed by users only in the process of use or in the aftermath of consumption. All types of services are thereby categorised as experience goods. See Nelson, Phillip. "Information and consumer behaviour." Journal of political economy 78, no. 2 (1970): 311-329.

[535] "Credence goods" refer to the goods whose risk can only be sensed after a period. See Darby, M. R., & Karni, E. (1973). Free competition and the optimal amount of fraud. The Journal of law and economics, 16(1), 67-88.

[536] See Bakos, Yannis, Florencia Marotta-Wurgler, and David R. Trossen. "Does anyone read the fine print? Consumer attention to standard-form contracts." The Journal of Legal Studies 43, no. 1 (2014): 1-35; see also Kaufmann, Walter. GOING BY THE BOOK: THE PROBLEM OF REGULATORY UNREASONABLENESS. Routledge, 2017.

[537] It is noticed that information regulation only includes voluntary standards, but does not contain any type of mandatory standards. Mandatory standards in theory are independently categorised. See Ogus (2004), supra note 526, at 190-191.

[538] See Ogus (2004), supra note 526, at 214.

requirement for prior approval prevents parties from engaging in activities unless they have been scrutinised by regulators. In this sense, prior approval serves as the most stringent type of regulation, and authorities endorse its function in disclosing information.

In Europe, under the "New Legislative Framework"[539], many notified bodies are responsible for assessing the conformity of certain products before they are placed on the market.[540] These notified bodies have to perform in a non-discriminatory, transparent, neutral, independent and impartial way.[541] In addition, the qualified bodies have to employ competent personnel with sufficient knowledge and expertise to accomplish the conformity assessment.[542] Therefore prior approval, in theory, is considered to be superior when it comes to disclosing the safety information of products where there is a degree of technical complexity.

Prior approval has a direct deterrence on the parties that intend to enter the particular market. Once a licence is granted to a producer, it is assumed that sufficient and reliable safety information is disclosed to consumers. However, the application of prior approval may not be inherently justified. Firstly, prior approval has been criticised due to its prohibitive *administrative cost*.[543] Authorities have to invest considerable efforts in checking each application. Secondly, prior approval might impede *innovation*. In this regard, the possibility that a product may not be granted a licence (in

[539] Adopted since 2008, the "New Legislative Framework" is a regulatory regime to stimulate product safety in the EU. It consists of several regulatory mechanisms ranging from prior approval to market surveillance. For general information, see the official website: https://ec.europa.eu/growth/single-market/goods/new-legislative-framework_en. Visited on December 2nd 2018.

[540] The list of notified bodies can be found on the NANDO website (see, https://ec.europa.eu/growth/tools-databases/nando/). Visited on December 2nd 2018.

[541] See Article R15(2) and Article R17(3) of the Decision 768/2008/EC. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008D0768. Visited on December 2nd 2018.

[542] See Article R15(6) of the Decision 768/2008/EC.

[543] See Ogus (2004), supra note 526, at 214-215.

time) will reduce the incentive for producers to invest in R&D.[544] Thirdly, prior approval might lead to an *anticompetitive* effect by excluding some parties from the market.[545]

To conclude, despite its function of reducing information problems, given the issues mentioned, the scope of prior approval should be restricted to *hazardous activities*. If information disclosure is the sole goal, then a variety of other regulatory instruments are likely to be more desirable.

9.1.3. Mandatory Standard

Mandatory standards are situated somewhere between prior approval and information regulation. Compared with prior approval, relevant parties do not need to get permission prior to undertaking particular activities. Compared with information regulation, standards impose a behavioural requirement on the involved parties in addition to setting disclosure requirements.[546]

In theory, mandatory standards can target specific hazardous outcomes (i.e., the so-called “target standards”), control production behaviour (i.e., the so-called “performance standards”) or even specify the methods and materials used in production (i.e., the so-called “specification standards”). By directly requiring producers to comply with specific requirements, mandatory standards are considered to be a way of significantly reducing the cost to consumers of analysing the collected information.

If mandatory standards can reduce the cost of consumers for assessing product risk and reduce consumer errors, why do they not replace information regulations? A brief explanation is that the cost of creating standards can be exceedingly high and can even exceed the potential benefits offered by them. In particular, various costs are generated in the process of making standards. Firstly, like adopting the regime of prior approval, regulators have to bear a massive administrative

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[544] For example, literature shows that a great decline in the number of new drugs resulted after the 1960s in the US, when the licensing system was included into the drug regulation. In comparison, this effect was not observed in the UK, where a post-marketing regime dominated drug regulation. See Grabowski, Henry G., and John M. Vernon. “Consumer protection regulation in ethical drugs.” The American Economic Review 67, no. 1 (1977): 359-364; see also Schifrin, Leonard G. “Lessons from the Drug Lag: A Retrospective Analysis of the 1962 Drug Regulations.” Harv. JL & Pub. Pol'y 5 (1982): 91. For the recent studies on this topic, see Lietzan, Erika. “The Drug Innovation Paradox.” Mo. L. REv. 83 (2018): 39.

[545] See Ogus (2004), supra note 526, at 214.

[546] See Ogus (2004), supra note 526, at 150-151.

cost to formulate standards and they may misunderstand the information collected by them.[547] Unlike information regulations, in which private parties detect and disclose information, with mandatory standards, it is the regulators that have to collect sufficient information and analyse it impartially. In a market where the preference of consumers is heterogeneous and the range of products is enormous, it would very costly for public agencies to formulate mandatory standards to the level of detail required.[548] On the other hand, once a standard is issued, private parties face a high compliance cost to adjust their production. In this regard, they have to purchase devices as well as carry out safety measures to meet the requirements of the standards. Therefore, taking the cost of making mandatory standards into account, the ones with fewer interventions (e.g. target standards) seem to be more desirable.

In practice, as observed with the adoption of prior approval, mandatory standards, especially those with a higher level of intervention (e.g. specification and performance standards), could also result in an anti-competition effect.[549]

9.1.4. Summary

By applying various information regulations, mandatory standards and prior approval, not only are consumers provided with sufficient information to make decisions efficiently but any downstream parties can also assess the safety level of their upstream suppliers. This last subsection summarises the findings and provides some implications for how to use regulations effectively in specific scenarios.

Prior approval is a double-edged sword. On the one hand, it directly excludes specific parties from entering the market, which precludes some risk from the outset. On the other hand, it may impede innovation and go against the heterogeneity of consumer preference, and even gives rise to an anti-competition effect. Therefore, the scope of prior approval should be limited to extremely risky activities, especially in cases where private laws do not efficiently offer the deterrence. In the areas, such as medical devices, food and chemical products, prior approval would play an important role

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[547] See Coglianese, Cary, Richard Zeckhauser, and Edward Parson. "Seeking truth for power: Informational strategy and regulatory policymaking." Minn. L. Rev. 89 (2004): 277.

[548] See Viscusi, W. Kip. (1984). REGULATING CONSUMER PRODUCT SAFETY. American Enterprise Institute.

[549] See Ogus (2004), supra note 526, at 198-199.

in reducing accidents. In other words, instead of serving as a signal of product safety, the primary goal of prior approval is to correct externalities that are not adequately corrected by private laws.

Mandatory standards cover a great variety of regulations. These regulations could be quite different regarding their goals and may result in different effects. Therefore, the question on the extent to which a mandatory standard applies should be answered in concrete scenarios. Firstly, in the situation where the information on *product materials* is more important in the evaluation of consumers, specification standards are desirable. What is more, in the situation where product safety is mainly determined by the *behaviours* within the production process, performance compliance is more valuable to consumers. Furthermore, in most other cases, target standards, as the lowest level of intervention, apply.

Information regulations are less sensitive to the side effects that be caused by prior approval or mandatory standards. In the cases where the heterogeneous preference of consumers or the broad scope of products is valued, but the information is insufficiently accessible to consumers, regulators may require the party with more private information to reveal such information mandatorily.

9.2. The regulatory regime in the context of 3D printing

In practice, regulations play a role in the circumstances where personal bargaining fails to provide producers with the incentive to take optimal precautions. Recent decades have witnessed the rise of regulations on the private bargaining related product risk. An early attempt was the Magnuson-Moss Warranty Act, which was promulgated in the US in 1975. The most prominent characteristic of this Act is that it established the guidelines that require producers to comply with them and to ensure that consumers could understand the provisions of warranties in an unambiguous way.[550]

Legal interventions in the contractual relationship are also observed in Europe. For instance, producers have to meet a wide range of mandatory performance and specification standards. Apart from that, they are required to disclose particular information by law. The main interest of this section is therefore to discuss the extent to which CAD file makers and fabricators are subject to

[550] Agrawal, Jagdish, Paul S. Richardson, and Pamela E. Grimm. "The relationship between warranty and product reliability." Journal of Consumer Affairs 30, no. 2 (1996): 421-443.

these relevant regulatory mechanisms and more importantly, whether these regulatory methods could offer additional incentives to actors to behave appropriately.

9.2.1. Mandatory standards for sellers: the CSGD and the CSD

In 1999, the European Consumer Sales and Guarantee Directive (the "CSGD")[551] was promulgated in the EU. The purpose of the CSGD is twofold: to ensure the free movement of goods within the Community and to achieve a higher level of consumer protection across Europe.[552] The conformity of the sales contract between the seller and the consumer is also emphasised in the directive. These requirements have been largely maintained in the new European Consumer Sales Directive (CSD) that was adopted in 2019. It is expected to replace the current CSGD by 2022.[553] The content of this section is thus organised to discuss how the provisions in the current CSGD and the new CSD are formulated to regulate the behaviour of CAD file makers and fabricators.

Firstly, according to Article 2(1) of the current CSGD, any seller in the chain of contracts is required to behave in conformity with the contract. Several basic *requirements* related to the performance of a seller must be fulfilled: (1) the product shall match the product description given by the seller; (2) the product shall be fit for the purpose agreed by the seller and consumer in the conclusion of the contract; (3) the product shall be fit for the purpose for which products of the same type are normally used and (4) the product shall show the quality and performance that is normal in products of the same type.[554] In the new CSD, these requirements are retained, and they are distinguished into the subjective and objective groups.[555] Whenever consumers confront any of the above non-conformities, they have a bundle of rights to claim against.[556]

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[551] DIRECTIVE 1999/44/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 May 1999 on certain aspects of the sale of consumer goods and associated guarantees. OJ L 171.

[552] Article 1 of the CSGD, Directive 1999/44/EC.

[553] Article 23 of the CSD, Directive 2019/771.

[554] Article 2 of the CSGD, Directive 1999/44/EC.

[555] Article 5-8 of the CSD, Directive 2019/771.

[556] According to Article 3 of the current CSGD, the contents that a consumer can require are repair or replacement, an appropriate reduction of the price or rescinding the contract.

The conformities in the CSGD and the CSD indicate that sellers in the chain of contracts are required to provide consumers with *legal warranties*.[557] In other words, in contrast with commercial warranties that are offered voluntarily by a seller or producer, the effects of these legal warranties are directly established by law and thus, can neither be waived by domestic laws nor by private agreements.[558]

The duration of these legal warranties is fixed in the CSGD. According to Article 5 of the current CSGD, consumers can claim their rights in respect of non-conformity within two years from the time of delivery.[559] If the product is a second-hand product, the period should not be less than one year.[560] Applying a fixed period can reduce the transaction cost, provided that the demands are homogeneous. However, in the circumstances that the preferences of the consumers are heterogeneous, the fixed period could frustrate consumers.[561] In particular, the preferable length of a warranty is influenced by several objective factors, ranging from the state of the technical development to the lifespan of a product, as well as subjective factors like the information asymmetry between sellers and consumers.[562]

To conclude, a statutory warranty with a fixed minimum period is a double-edged sword. On the one hand, by forcing producers to comply with specific behaviour standards, it promises a higher level of consumer protection. In doing so, the CSGD and CSD provide producers with an incentive to increase precautionary levels by meeting the required standards. On the other hand, since the information possessed by regulators may not accurately reflect the heterogeneous preferences and attributes of consumers, the scope as well as the duration may not result in an inefficient outcome.

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[557] In literature, several terms are used to represent the conformities required by law. They are statutory warranties, mandatory warranties and legal warranties. There is no essential difference between them.

[558] See Article 7(1)(a) of the CSGD, Directive 1999/44/EC.

[559] The two-year period is also transplanted into the domestic laws by the majority of countries. In addition, several countries offer a short period. For example, Sweden adopts a three-year period legal warranty for all types of products. In Norway and Iceland, for a product having a long lifespan (e.g. cars and expensive furniture), a five-year period of legal warranty is adopted.

[560] See Article 7(1)(b) of the CSGD, Directive 1999/44/EC.

[561] Van den Bergh, Roger, and Louis LT Visscher. "Consumer Sales Law from an Economic Perspective." (2009), at 10.

[562] Ott, Claus, and H. B. Schäfer. THE ECONOMIC ANALYSIS OF CIVIL LAW. Cheltenham, UK: Edward Elgar Publishing, 2004, at 350-351.

9.2.2. Mandatory standards in the digital age: the EDCD

At the time when the CSGD was issued, goods that were in digital formats were not linked with harms. As a result, the scope of goods is limited to being either *tangible* or *movable* in this directive.[563] Against this background, the past two decades have witnessed the increase in e-commerce, and life is now comprehensively linked with digital products. These products have the capacity to determine, to a substantial extent, the quality and function of physical products. In this regard, sellers and consumers are inclined to enter contractual relationships to allocate the potential risk generated by digital content. However, considering the complexity of the Internet, it could be even more difficult for a consumer to understand the information on a product. As a result, the seller trading digital goods could be under-deterred by contracting for product risk. Thus, legal interventions have also been introduced in this context to ensure that information asymmetry can be eliminated and that the contractual parties are incentivised to optimise their activities.

One legal intervention is to impose mandatory conformity requirements on traders of digital products. On 15th April 2019, a specific directive on contracts for supplying digital content and services[564] was issued (the European Digital Contract Directive, i.e., the EDCD), the goal of which was to give consumers better access to digital content and services.[565] Traders that run businesses with a wide range of digital content and services are subject to this directive. Digital content and services can be divided into three categories: (1) data produced and supplied in digital form;[566] (2) services allowing consumers to create, process, store, or access data in digital form[567] and services allowing the sharing of data[568]; and (3) durable media exclusively used for incorporating digital

[563] According to Article 1(2)(b) of the current CSGD (1999/44/EC), goods mean "any tangible movables". This definition is followed by the new CSD (2019/771/EU). Article 2(5)(b) also stresses that goods with digital content are also categorized as digital goods. However, pure digital content and services are not counted in.

[564] Directive on Contracts for the supply of digital content and digital services: Position of the European Parliament of 26 March 2019 and Council decision of 15 April 2019 (not yet published in the Official Journal). Available at: https://ec.europa.eu/info/business-economy-euro/doing-business-eu/contract-rules/digital-contracts/digital-contract-rules_en.

[565] Recital (1) of the preamble of the EDCD.

[566] See Article 2(1) of the EDCD. The typical case is online video and music.

[567] See Article 2(2)(a) of the EDCD. The typical case is cloud storage.

[568] See Article 2(2)(b) of the EDCD. The typical case is the digital content sharing platform, such as YouTube.

content.[569] In comparison, a physical good with a digital component, which is exclusively used as a carrier, will still be regarded as a tangible movable asset. Therefore, it is subject to the CSGD but not the EDCD.

The EDCD shares many similarities with the CSGD. First and foremost, consumers can claim their rights only against the trader that is in a contractual relationship with them. Second, the conformity requirements only apply to the contract where a consumer "pays a price" for the digital content and service supplied by the trader.[570] In other words, if a person downloads digital content *for free*, then the trader offering this digital content will not be subject to the mandatory conformities required by the EDCD. Third, a mandatory two-year warranty is adopted under the EDCD, so that consumers with a lower level of risk have to respect this minimum period and they cannot freely choose another period according to their preferences.

9.2.3. Information regulations in the context of 3D printing: the ECRD

Besides complying with the mandatory conformity standards, producers are also required by regulators to disclose critical information. European Consumer Rights Directive (ECRD)[571] was promulgated in 2011 to introduce specific legal interventions on information disclosure for distance contracts.[572]

According to the ECRD, the pre-contractual information should be provided to the consumer in a clear and comprehensive manner in distance contracts.[573] In particular, if a consumer is under the

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[569] See Article 2(3) of the EDCD. The typical case is the storage disk.

[570] Article 3(1) of the EDCD states that "this Directive shall apply to any contract where the trader supplies or undertakes to supply digital content or digital service to the consumer and the consumer pays or undertakes to pay a price."

[571] DIRECTIVE 2011/83/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 October 2011 on consumer rights, amending Council Directive 93/13/EEC and Directive 1999/44/EC of the European Parliament and of the Council and repealing Council Directive 85/577/EEC and Directive 97/7/EC of the European Parliament and of the Council. L 304/64.

[572] A distance contract refers to any contract concluded between the seller and contract with the exclusive use of a means of distance communication, such as mail order and Internet order. See Article 2 and Recital 20 of the ECRD, Directive 2011/83/EU.

[573] Eighteen types of information are specifically required to be provided by a digital product provider. See Article 6(1) of the ECRD, Directive 2011/83/EU.

obligation to pay, information on (1) the main characteristics of a product; (2) the total price of a product; (3) the duration of the contract; and (4) the minimum duration of a consumer's obligations should be explicitly disclosed to the consumer before the order is placed.[574]

In general, the ECRD distinguishes between four types of distance contract: sales contracts, service contracts, contracts for online digital content, and contracts for the supply of public utilities. A "sales contract" refers to "any contract under which the trader transfers or undertakes to transfer the ownership of goods to the consumer and the consumer *pays or undertakes to pay the price* thereof, including any contract having as its object both goods and services."[575] A "service contract" refers to "any contract other than a sales contract under which the trader supplies or undertakes to supply a service to the consumer and the consumer *pays or undertakes to pay the price* thereof".[576] In official documents, "contracts for digital content" are interpreted as supplying data in digital form and they are regarded "neither as sales contracts nor as service contracts".[577] Contracts for digital content are distinguished from sales contracts and service contracts, not only because they relate to supplying data in digital form but also because they do not discriminate the traders that undertake activities for free from the ones that trade for commercial purpose.

The difference between contracts for digital content and sales and service contracts further determines that the requirements for information disclosure are not equal for these different types of contract.

Since sales contracts and service contracts only refer to contracts where consumers *pay a price* for a product or service, the traders who offer tangible goods or services for free in distance contracts are thus excluded from the scope. As a result, traders that offer tangibles and service for free are not subject to the information disclosure requirement under the ECRD.

In comparison, in the definition of the contracts for online digital content,[578] traders that provide digital content for free are not distinguished from those that trade for commercial purposes.

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574 See Article 8(2) of the ECRD, Directive 2011/83/EU.

575 See Article 2(5) of the ECRD.

576 See Article 2(6) of the ECRD.

577 See Recital 19 of the ECRD.

578 "Digital content" means "data which are produced and supplied in digital form." According to the exposition of the EC, if a contract relates to the transfer of digital content through service, this contract is defined as the contract for

Therefore, all traders that offer online digital content are thus subject to information disclosure requirements under the ECRD without any distinction. In other words, the providers of free digital content must also meet information disclosure requirements. This interpretation is confirmed by the official guidance document of the EC.[579]

To summarise, in terms of information disclosure, without discriminating against the purpose of traders (as part of a monetary exchange or for free), the ECRD actually sets a higher standard for the providers of digital content than for other sellers or service providers. In other words, information disclosure is compulsory for all digital content producers but not for other non-digital sellers and service producers.

9.2.4. Concluding remarks

This subsection concludes on the findings on the issue of how various legal interventions are adopted to overcome the problems of contracting for product risk.

It can be seen that by making some conformity requirements mandatory in regulations, the transaction cost as well as information asymmetry is expected to be reduced to some extent. On the one hand, consumers with homogeneous attributes and preferences do not need to bargain over the product risk each time. On the other hand, sellers are forced by regulators to increase the level of precaution despite consumers holding few information in specific circumstances.

This subsection also reviewed the specific legal interventions which are related to concluding a contract for digital products. The analysis showed that mandatory conformities with a minimum of a two-year period are required and that traders are required to disclose consumer-specific information on the digital product in a comprehensive manner.

In general, a trader that offers a product (either in digital or tangible format) will fit into one of the four circumstances summarised in Table 9. To briefly summarise from a positive legal perspective,

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digital content but not as service contracts. The European Commission. DG Justice Guidance Document concerning Directive 2011/83/EU of the European Parliament and of the Council of 25 October 2011 on consumer rights, amending Council Directive 93/13/EEC and Directive 1999/44/EC of the European Parliament and of the Council and repealing Council Directive 85/577/EEC and Directive 97/7/EC of the European Parliament and of the Council. 2004, at 5. (Hereinafter the “Guidance Document on ECRD”).

[579] See EC (2014), supra note 578, at 8.

for sales and service contracts that focus on the transfer of ownership of tangible goods or offering services (not concerning digital content), (A) if a trader offers a product for a monetary purpose, then its behaviour should not only be in conformity of the requirements under the CSGD but it also has to offer the information required by ECRD. In comparison with the aforementioned situation, (B) if a trader transfers a tangible good or provides related services for free, then neither the legal warranties nor the information disclosure required by the current legal regime are imposed on it. For digital goods, (C) if a trader offers paid-for digital content, then the trader is not only subject to the legal warranties under the EDCD but it must also offer the information required by the ECRD. In comparison to the situation C, (D) if a trader supplies digital content for free, then the trader is not subject to the conformity requirements under the EDCD but it still needs to offer the information required by the ECRD.

Table 9: Mandatory conformity and information regulations in various scenarios

Type	Scenario	Mandatory conformity?	Information disclosure?
A	Selling goods or offering services	Yes (CSD)	Yes (ECRD)
B	Offering goods or services for free	No	No
C	Selling digital content	Yes (EDCD)	Yes (ECRD)
D	Offering digital content for free	No	Yes (ECRD)

9.3. Mandatory conformity and information disclosure in the context of 3D printing

The discussion in the last subsection indicates that while legal interventions may improve personal bargaining by forcing traders to offer warranties and to disclose information mandatorily, their effect rests on the business model established in the particular context. From a positive legal perspective, the conformity and information disclosure requirements confronted by a trader could be distinguished into four categories.[580] If we apply this framework to the context of 3D printing, the concrete business models operating to capture the value added by 3D printing can be linked to a particular scenario. As a result, the extent to which specific CAD file designers and fabricators are subject to these statutory requirements is summarised in Table 10 as below:

Table 10: Mandatory conformity and information regulations in 3D printing

Type	Scenario	Mandatory conformity?	Information disclosure?
A	Model B.1, Model B.2, Model B.3	Yes (CSD)	Yes (ECRD)
B	-	No	No
C	Model A.2, Model A.3	Yes (EDCD)	Yes (ECRD)
D	Model A.1	No	Yes (ECRD)

As shown in Table 10, the requirements of mandatory conformity and information disclosure are not only expected to play a role in the business models where parties are able to well bargain over the product risk (e.g. Model A.3, Model B.1 and Model B.3), but its application also implies some improvement of social welfare in the business models where the involved parties are unable to efficiently bargain over product risk (e.g. Model A.1, Model A.2 and Model B.2). In this regard, it is reasonable to estimate that regulations are necessary to improve the deterrence effect, especially in the scenarios where contractual relations turn to be a failure.

The following analysis of this section will focus on the deterrence effect contributed by regulations in the business models where contract relation fails.

[580] See the summary in Table 9.

9.3.1. The role of regulations under Model A.1

As shown in Table 10, the function of legal interventions under Model A.1 is twofold.

Firstly, mandatory warranties are not applicable in this context. According to Article 3(1) of the EDCD, the trader of free digital content is not subject to the conformity requirements.[581] Also, a trader that offers software under a free and open-source licence is excluded from bearing the mandatory warranties required by the directive.[582] Therefore, any party (including the final trader) that contributes to a CAD file and re-uploads it online for free is not subject to the mandatory conformity requirements. This means that the hundreds of thousands of parties who are active on open-source platforms like *Thingiverse*, are exempted from the mandatory conformity requirements. Therefore, legal warranties offer no incentive to CAD file designers under Model A.1.

Secondly, CAD file designers under Model A.1 cannot escape the requirement for information disclosure. In particular, these parties should at least provide the information required by Article 6(1) of the ECRD in a clear and comprehensive way on the website.[583]

To summarise, under Model A.1, with the information disclosed at the requirement of ECRD, a consumer is expected to better evaluate the risk of a product before downloading the CAD file from an open-source platform. The disclosure of information in return will incentivise the CAD file designer to improve their behaviour to some extent.

9.3.2. The role of regulations under Model A.2

Unlike Model A.1, in which the CAD files are supplied to consumers for free, a consumer must *pay a price* for a CAD file under Model A.2. This significant difference indicates that, besides the requirement of information disclosure, legal warranties are applicable in this context.[584]

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[581] Article 3(1) states that "this Directive shall apply to any contract where the trader supplies or undertakes to supply digital content or digital service to the consumer and the consumer pays or undertakes to pay a price."

[582] See Article 3(5)(f) of the EDCD.

[583] See Article 8 of the ECRD.

[584] See Article 3(1) of the EDCD.

A trader who sells CAD files in an online marketplace should not only behave consistently with what they promise in that contracts, but the CAD file offered must also conform to the objective requirements. In particular, the CAD file provided by a digital designer should satisfy the requirements under Article 8 of the EDCD. For example, a CAD file trader should ensure that the CAD file is fit for regular use, that the quality and performance of the CAD file fits the reasonable expectation of a consumer, and that the consumers are informed of any safety update.

To summarise, regulatory interventions may contribute to product safety under Model A.2 by forcing CAD file designers to comply with mandatory standards and requiring these parties to disclose the necessary information.

9.3.3. The role of regulations under Model B.2

In the new CSD, mandatory conformities apply to the *sales contracts* between the consumers and sellers.[585] A sales contract refers to "any contract under which the seller transfers or undertakes to transfer ownership of goods to a consumer, and the consumer pays or undertakes to pay the price thereof."[586] In this regard, the party who offers a printing service to consumers is subject to the mandatory conformities required by the CSD.[587] The difference in this decision will provoke quite different deterrence effects. If the contract concluded between the fabricator and consumer is defined as a sales contract, then the fabricator would be incentivised to make an investment in precautionary measures.

The information disclosure requirements under the ECRD still apply to fabricators under Model B.2. In this sense, no matter whether the contract concluded between the fabricator and consumer is defined as a sales contract or a service contract, the fabricator is obliged to provide the consumer with particular information in a clear and comprehensible way.[588] However, it should be noted that when it comes to 3D printing, the information that should be disclosed under ECRD is currently quite basic.

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585 See Article 3(1) of the CSD, Directive 2019/771/EU.

586 See Article 2(1) of the CSD, Directive 2019/771/EU.

587 The conformities are seen in Article 6-8 of the New CSGD, Directive 2019/771/EU.

588 See Article 1(2)(c) of the ECRD, Directive 2011/83/EU.

To conclude, the analysis above implies that as the CSD and the ECRD apply to the fabricators under Model B.2, the fabricators who run a business there would be induced to comply with the mandatory standards and disclose more information accordingly. As a consequence, it is reasonable to expect that the regulatory regime based on the CSD and the ECRD may result in a higher level of social welfare, since fabricators under Model B.2 have to meet some mandatory standards required by law. As a result, consumers are able to access more of the information disclosed by fabricators in support of their decisions.

9.4. Chapter conclusion

When consumers are unable to correctly evaluate the cost of an accident with the utilities under private laws, regulations play a residual role in improving the effect on deterrence when consumers are unable to correctly evaluate the cost of accident with the utilities under private laws. The analysis in this chapter confirmed that CAD file makers and fabricators are indeed subject to specific performance standards and information regulations. Regulations are also found to improve the deterrence effect. Especially, under the business models where the parties involved cannot efficiently contract over the product risk (e.g. Model A.1, Model A.2 and Model B.2), the function of regulations is even more prominent.

In practice, besides mandatory standards and traditional information regulations, other kinds of regulations are also underway. For example, CAD file makers are encouraged to apply for pertinent certificates endorsed by various standardised bodies like ISO and CEN. In addition, prior approval is also suggested to apply to hazardous products, such as medical devices, food and particular mechanical tools.

Chapter 10. Platform Governance as a Complementary Instrument in the Context of 3D Printing

Introduction

In recent years, the transformation of the value chain has led to more digital content and services being transferred onto platforms.[589] The increase of the platform economy is also observed in the context of 3D printing. One of the most prominent similarities among the business models lies in in the fact that an intermediary platform is indispensable for CAD file makers and fabricators to use to run their businesses and to reach out to consumers. In particular, under Model A.1, the platform offers a community where user-generated CAD files are shared. Under Model A.2 and Model B.2, the platform serves as an online marketplace, where a number of individual CAD file makers or fabricators can run their small business. In all of these circumstances, platforms have a chance to closely observe the activities of the CAD file makers and fabricators as well as the consumers.[590] Under this background, whether or not the platform can be relied upon to achieve the goal of deterrence and risk-shifting is the core issue that will be discussed in this chapter.

[589] Traditionally, "platform" mainly refers to the cyberspace where user-generated contents are shared". See Gillespie, Tarleton. "The politics of 'platforms'." New media & society 12, no. 3 (2010): 347-364; see also Helmond, Anne. "The platformization of the web: Making web data platform ready." Social Media+ Society 1, no. 2 (2015). The scope of platform is broad in literature, where it generally dictates the companies who run an online business. See Srnicek, Nick. PLATFORM CAPITALISM. John Wiley & Sons, 2017. According to EU documents, online platforms are concerned to share key characteristics including "the use of information and communication technologies to facilitate interactions (including commercial transactions) between users, collection and use of data about these interactions, and network effects which make the use of the platforms with most users most valuable to other users." See https://ec.europa.eu/digital-single-market/en/glossary#Online_Platforms. Visited on May 15th 2019.

[590] Lobel, Orly. "Coase and the platform economy." in John J. Infranca (ed.) CAMBRIDGE HANDBOOK OF THE LAW OF THE SHARING ECONOMY, Cambridge University Press, 2018, at 67-77.

The way that a platform undertakes certain strategies to govern the cyberspace ecosystem is called "platform governance".[591] In general, platform governance may improve social welfare in two ways. On the one hand, by developing various mechanisms, platform governance may provide the relevant parties with an extra incentive to take precautions. On the other hand, by aggregating a large number of CAD file makers and fabricators, the platform may play a role in risk-shifting by designing a risk-shifting mechanism to spread the losses among all of the members.

10.1. The impact of platform governance on deterrence

Platform plays an increasingly important role in the digital age. For individuals and SMEs who cannot afford an independent supply channel, intermediary platforms are the most affordable way for them to show their business. In practice, platforms may develop different mechanisms to reduce the product risk. This section discusses the mechanisms that have been adopted or that can be developed by intermediary platforms to achieve the goal of deterrence.

In general, platform governance has an impact on deterrence through two approaches. On the one hand, the platform can set up specific entry requirements and codes of conduct for the parties who are willing to run a business on the platform. In doing so, in order to establish a business on a specific platform, CAD file makers or fabricators are directly provided with an incentive to employ the required precautionary measures. On the other hand, platforms may adopt various mechanisms to signal the safety of various CAD file makers and fabricators. Consumers may distinguish the actors with a higher risk from the ones with a lower risk, so they are expected to make better consumption decisions.

[591] See Van Dijck, José, Thomas Poell, and Martijn De Waal. THE PLATFORM SOCIETY: PUBLIC VALUES IN A CONNECTIVE WORLD. Oxford University Press, 2018, at 5. On the other hand, platform governance is used to indicate how a platform is governed. In this sense, it copes with the issue of how to provide platforms with the incentive to behave accountably. Taking all these facets into consideration, from a broad viewpoint, platform governance refers to "the systems of rules, norms, and civic labour governing an online community." See Matias, J. Nathan, and Merry Mou. "CivilServant: Community-led experiments in platform governance." In Proceedings of the 2018 CHI conference on human factors in computing systems, at 9. ACM, 2018.

10.1.1. Platform governance: from commons to clubs

A platform can intervene in the deterrence effect through two approaches. One is setting up particular *entry requirements* to preclude risky actors from entering specific commons. The other is establishing a bundle of *codes of conduct* to supervise the behaviour of involved actors once these parties start to run businesses on the platform.

Platform governance: entry requirements

In essence, the platform offers a "commons" where the supply and demand can meet with each other. In a circumstance where no externalities are posed by the platform economy, legal interventions are unnecessary. However, with the increasing product risk, there is a pressing need to establish some pertinent rules to govern the commons. One of the measures adopted by the operator of the platform is to set up specific entry requirements for becoming a member of the platform. In doing so, the platform is de facto transformed from a "commons" to a "club".

The entry requirements could be largely different in practice. In the context of 3D printing, the threshold of establishing a business on a platform could be extremely low in some circumstances. For example, in most cases under Model A.1, Model A.2 and Model B.2, what a CAD file maker or fabricator needs to do is simply to register an account and offer the necessary information, such as the type of 3D printers used and the lead time. In comparison, the threshold of other platforms could be somewhat higher. The typical case is Model B.3, in which a fabricator can only be permitted to set up business there if multiple requirements are satisfied. The following analysis uses *3D Hubs* as an example to illustrate how the platform could induce fabricators to take precautionary measures by setting up higher entry requirements.

3D Hubs transformed from Model B.2 to Model B.3 in 2017. Before 2017, many hubs operated by a variety of parties were placed on *3D Hubs'* website. As Figure 19 illustrates, hundreds of thousands of private hubs could be found by a CAD file holder on *3D Hubs* before it changed its business model.[592] Based on this model, *3D Hubs* was already a success. By 2017, more than a

[592] This image is a snapshot that was made in 2017. At the moment, the original webpage cannot be opened anymore.

million components had been printed by fabricators on the platform. In addition, three rounds of funding were completed with more than $29.5 million invested in this start-up.[593]

Figure 19: The distribution of 3D printers around the world (3D Hubs, before 2018)

During the period between 2017 and 2018, *3D Hubs* undertook a business model transformation. Several actions were taken by the platform operator. In general, the requirement to register as a fabricator on *3D Hubs* became more stringent. Firstly, fabricators that employed only desktop 3D printers could no longer run a business on *3D Hubs*. In this sense, a fabricator has to invest in industrial-level 3D printers in order to be visible on *3D Hubs*.[594] A direct result of this shift was that the number of fabricators reduced tremendously. Secondly, a fabricator that wants to place the business on *3D Hubs* now has to obtain the ISO certification. Thirdly, the printing process must be fulfilled by the fabricator itself, which means that outsourcing is not allowed. In addition,

[593] See: https://www.crunchbase.com/organization/3d-hubs#section-overview. Visited October 8th, 2019.

[594] According to an open letter from a fabricator that used to operate his business on 3D Hubs, the accounts of most individual fabricators were shut down around 2017. See: https://www.reddit.com/r/3Dprinting/comments/747slw/3dhubs_is_dead/. Visited on June 15th, 2018.

consumers and fabricators under the new business model are no longer matched on the basis of free bargaining. Instead, consumers and fabricators are matched by *3D Hubs*.

There are different opinions about the action taken by *3D Hubs* to shift the business model from Model B.2 to Model B.3.

3D Hubs is considered to have assumed scale on its own by setting up higher entry requirements. In other words, the nature of its business model has shifted from a commons to a club. Under this arrangement, a lot of individual fabricators complained that their investments were not respected by *3D Hubs*, since it failed to alert its users ex-ante. For example, a fabricator that had purchased thirteen 3D printers since 2014 accused *3D Hubs* of "despicable and immoral" business practices.[595]

Despite the criticisms, there are some private considerations from *3D Hubs'* point of view. Firstly, adjusting the business model from Model B.2 to Model B.3 was thought to be necessary for the purpose of boosting the business. After embracing Model B.3, *3D Hubs* successfully raised further capital. In addition, according to data from *3D Hubs*, the number of transactions has increased significantly since the transformation.[596] The CEO claimed that more than 1 billion parts could be printed as a result of the adjusted business model.

Quality assurance has also been introduced into the business model transformation of *3D Hubs*, which is deemed to be a positive signal related to improving product safety. Firstly, *3D Hubs* only allows fabricators that are certified by ISO standards to be its partners. In addition, all the partners have to go through a strict onboarding process conducted by *3D Hubs* before they are added to the partner network. Secondly, *3D Hubs* carries out an additional inspection once the product is ready to ensure that it meets the quality standards. The final product thus reaches the consumer with an inspection checklist (See Figure 20) offered by *3D Hubs*.

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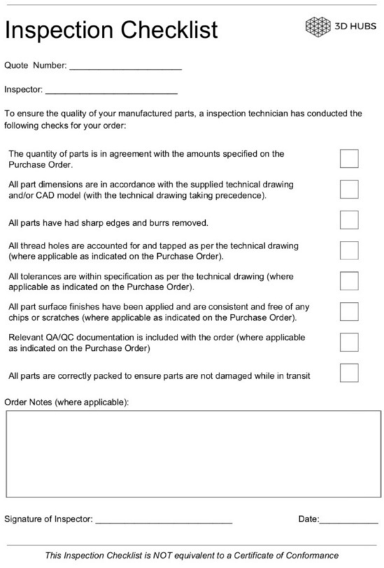
[595] To see the full text written by the former fabricator of 3D Hubs, see: https://www.reddit.com/r/3Dprinting/comments/747slw/3dhubs_is_dead/. Visited on June 15th, 2018.

[596] According to 3D Hubs, around 1 million parts were printed out by the fabricators in 3D Hubs. In comparison, this figure doubled within a year after adjusting the business model.


Inspection Checklist

3D HUBS

Quote Number: ____________________

Inspector: ______________________

To ensure the quality of your manufactured parts, a inspection technician has conducted the following checks for your order:

- The quantity of parts is in agreement with the amounts specified on the Purchase Order. ☐
- All part dimensions are in accordance with the supplied technical drawing and/or CAD model (with the technical drawing taking precedence). ☐
- All parts have had sharp edges and burrs removed. ☐
- All thread holes are accounted for and tapped as per the technical drawing (where applicable as indicated on the Purchase Order). ☐
- All tolerances are within specification as per the technical drawing (where applicable as indicated on the Purchase Order). ☐
- All part surface finishes have been applied and are consistent and free of any chips or scratches (where applicable as indicated on the Purchase Order). ☐
- Relevant QA/QC documentation is included with the order (where applicable as indicated on the Purchase Order) ☐
- All parts are correctly packed to ensure parts are not damaged while in transit ☐

Order Notes (where applicable):

Signature of Inspector: ________________________ Date:___________

This Inspection Checklist is NOT equivalent to a Certificate of Conformance

Figure 20: The checklist guaranteed by the 3D Hubs

To summarise the product safety implications, as the shift from Model B.2 to Model B.3 involves the platform entering into a contractual relationship with the CAD file maker, the platform has to bear some responsibility that it have promised to consumer. In essence, the role of the platform in Model B.3 is exactly the same as a traditional distributor or final seller. It does not undertake any substantive production activities, and its main task is to deliver a customised product to the consumer. Therefore, a linear supply (contractual) chain is established in Model B.3 and the responsibility of the platform is restricted to the conformity that has already been embedded into the contract between the end-consumer and itself.

It should be noted that platform governance by setting up entry requirements might contradict the private interest of the operator of the platform. For example, under Model A.1, the intermediary platform serves as an open-source community. The primary goal of setting up such an online platform is to ensure that individuals can share their innovative ideas as quickly as possible.

Therefore, the operator of the platform is reluctant to set up a stringent ex-ante threshold to prevent parties from uploading CAD files to the community. In other words, the operator of the platform is willing to operate the platform in a way to maintain it as an active commons as much as possible, even though the goal of boosting innovation might be achieved at the expense of exposing negative externalities to the society.

Platform governance: codes of conduct

An intermediary platform under Model A.2 and Model B.2 is characterised as a channel and virtual marketplace to connect suppliers with the demands. In practice, even though the platform is not qualified as the "seller" and it may not be subject to liability in the end, it has an incentive to monitor the behaviour of registered fabricators. This is because the accident caused by the fabricators on the platform would lead the consumers to other platforms.[597] In practice, a platform serving as an online marketplace of offering CAD files and printing services may adopt various measures to make it as a place to offer safe transactions, the most important one of which is developing various codes of conduct.

Treatstock is a typical online marketplace where a great number of individual fabricators list their 3D printing businesses. In order to ensure that producers are incentivised to behave appropriately, *Treatstock*, in its terms and conditions, shows the extent to which a fabricated product is defined as defective. For example, a product would be defined as defective if its parts shift along the X or Y axis or if the product is not straight or come apart over time.[598] Therefore, while a fabricator is not excluded from operating a business on the *Treatstock* platform, it has to respect the code of conduct made by the platform. If a specific party fails to comply with the particular standards presented, s/he might be punished by the platform at a later stage.

In brief, by developing a pertinent code of conduct, the platform aims to restrict the activities of its members. The implementation of the code of conduct is expected to offer a better incentive to the parties who cannot find alternative platforms. In contrast, provided that a CAD file maker or a

[597] See Twigg-Flesner (2015), supra note 291, at 54.

[598] The full text of warranties could be seen in "Appendix A" of Treatstock Terms and Conditions. Available at: https://www.treatstock.com/site/terms.

fabricator can easily shift from one platform to another that has adopted no code of conduct, the risk caused by these parties would still be externalised. In essence, both the code of conduct and entry requirements are instruments that the members of the platform have to respect. In practice, if the number of platforms with bad platform governance accounts for the majority, then platform governance in general might not incentivise a wide range of actors to behave appropriately. Therefore, to ensure the effect of platform governance in terms of deterrence, additional legal instruments should be offered to provide platforms with an incentive to improve their governance. In recent years, this consideration has been increasingly accepted across the EU. This issue will be discussed in Section 10.1.3.

10.1.2. Platform governance and information disclosure

Apart from the entry requirements and codes of conduct that are directly provided to CAD file makers and fabricators, the deterrence effect can also be improved by making sufficient information easily accessible to consumers. In practice, the cost of collecting and analysing information could be considerable.[599] Research has also shown that the performance of consumers on the assessment of information is reduced when they are overloaded with information.[600] As a result, the decision-making undertaken by consumers now heavily relies on the signals disclosed to them. Under the platform economy, a platform serves as a medium to guide consumers to meet suitable sellers. While this process could reduce the transaction cost to complete a transaction, a platform might influence the choice of consumers through the mechanisms set up by itself to filter and rank various sellers.

The discussion in this subsection provides some exemplary approaches that various platforms can adopt to disclose information. In addition, the underlying problems of each of these methods have been discussed.

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[599] See Hilbert, Martin. "Toward a synthesis of cognitive biases: How noisy information processing can bias human decision making." Psychological bulletin 138, no. 2 (2012): 211.

[600] See Eppler, Martin J., and Jeanne Mengis. "The concept of information overload: A review of literature from organization science, accounting, marketing, MIS, and related disciplines." The information society 20, no. 5 (2004): 325-344.

Information disclosure via categorisation

The simplest way to disclose information that every platform consciously or unconsciously adopts is categorisation. Categorisation refers to the method whereby a platform divides all businesses running on it into several categories. For example, on the popular online platform "eBay", all products are first separated into the categories of "electronics", "fashion" etc. Under the specific bundle of "electronics", all of the relevant goods are further categorised into "cameras", "computers", etc. All "cameras" are then distinguished by brand, series, warranties, battery type, delivery type etc. From the private interest perspective, categorising different designs and products under different titles is adopted mainly for the convenience of user searches. From the information disclosure perspective, categorisation is perceived as a process through which the platforms deliver useful information at the request of consumers. By narrowing down the conditions, not only will consumers be guided to the product that most closely adhere to their preferences, but they can also compare different providers as well. As a result, the decision-making by consumers is expected to be improved through categorisation.

Using categorisation to distinguish the safety of different services fits the context of 3D printing. At present, however, categorisation is very basic on 3D printing platforms. Taking *Thingiverse* as an example, all of the digital designs are only roughly categorised into ten groups. Beyond that, no further categorisation is offered. As a result, consumers have to make an extra effort to gain risk information about a CAD file or a product.[601]

In general, categorisation in nature is an instrument like a soft law. The platform can only be encouraged to implement it and there is presently no compulsory compliance.[602]

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[601] They are: 3D printing in general, art, fashion, gadgets, hobby, household, learning, models, tools, and toys and games.

[602] Cohen, Molly, and Arun Sundararajan. "Self-regulation and innovation in the peer-to-peer sharing economy." *U. Chi. L. Rev. Dialogue* 82 (2015): 116.

Information disclosure via a rating system

In addition to using categorisation, a rating system developed by a platform can also take the role of differentiating risks.[603] In this sense, it is the user who downloads a digital file or who has the experience of using a printed product that has the first-hand information on the advantages as well as the potential risks of a particular digital design or printed object. If they can share their experience on the platform, this information will help others to assess the potential risk.[604] At present, a number of platforms have embedded a rating system into their business models.[605] In an ideal situation, if every member of the platform shared their experiences in an accurate and non-biased way, the aggregated reviews could be perceived as a direct and visualised source of information. This would help insurers and other stakeholders to differentiate the risk present between the various individual producers.

The performance of the rating system, however, is constrained by several factors. Firstly, the rating system may only be helpful with designs and products that are repeatedly downloaded. It plays no role in the risk-differentiation of newly uploaded designs. Secondly, it is the users who decide whether to share their experiences. In other words, users may have no incentive to write a review.[606] Thirdly, a rating system could be biased.[607] In this regard, a negative review does not necessarily mean that the product is risky, and a positive review also does not necessarily indicate

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[603] Schreieck, Maximilian, Andreas Hein, Manuel Wiesche, and Helmut Krcmar. “The challenge of governing digital platform ecosystems.” In Claudia Linnhoff-PopienRalf SchneiderMichael Zaddach (eds.) DIGITAL MARKETPLACES UNLEASHED, Springer, Berlin, Heidelberg, 2018. 527-538.

[604] Milgrom, Paul R., Douglass C. North, and Barry R. Weingast. “The role of institutions in the revival of trade: The law merchant, private judges, and the champagne fairs.” *Economics & Politics* 2, no. 1 (1990): 1-23.

[605] In general, customers heavily rely on the reviews from other peers on the popular decentralized platforms such as Airbnb. The same model can also be observed on the platforms relating to decentralized 3D printing service. For example, the users of 3D Hubs can share their experience on the platform, which contribute to the community to a large extent.

[606] Reviews from the customers are precious data for online platforms, which can help them to adjust the business model and strategies. Therefore, platforms are incentivized to encourage their customers to review their experience by offering via different measures. For example, they can offer a coupon to the reviewers. See Mangold, W. Glynn, and Katherine Taken Smith. “Selling to Millennials with online reviews.” *Business Horizons* 55, no. 2 (2012): 141-153.

[607] See Tadelis, Steven. “Reputation and feedback systems in online platform markets.” *Annual Review of Economics* 8 (2016): 321-340.

that the product is safe.[608] In another case, the user may not have been exposed to a risk by the time s/he left the positive review. The harm may occur only after a long time, which indicates that a positive review may also not reflect the actual level of risk.

To conclude, the behaviour of consumers is also vital to the ecosystem of the platform. The general finding is that the safety information shown by the rating system is a double-edged sword. On the one hand, it provides subsequent consumers with first-hand information, which is based on real experience. On the other hand, the information offered by previous consumers might be exaggerated or biased. Recent empirical studies have also highlighted loopholes when using a rating system to differentiate risks.[609] Confronted with the information offered by rating systems, new instruments to assure the authenticity of the reviews are necessary. Therefore, the platform should not only establish a system to publish the information disclosed by previous consumers, but it should also construct a system (e.g. a notice-and-takedown mechanism) to correct information that is potentially wrong.

Information disclosure via ranking and filtering

Constrained by the limited time and ability to analyse the data, consumers are likely to make decisions based on the content that is first shown to them. In order to help consumers make decisions, platforms are developing extra settings in response to consumer demands.[610]

In recent years, with the advance of computer science, filtering and ranking are mostly accomplished by algorithmic systems. In general, an algorithm refers to a set of instructions that

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[608] For example, a risk may be posed to a user because s/he wrongly printed the design out or used the printed product despite the design itself having no defect at all. If this is the case, then the negative review cannot reflect the real condition of the design or product.

[609] For example, researchers indicate that consumers may not acquire a better quality, and they may be defrauded more often even if the product has been highly rated. See Jin, Ginger Zhe, and Andrew Kato. "Price, quality, and reputation: Evidence from an online field experiment." *The RAND Journal of Economics* 37, no. 4 (2006): 983-1005.

[610] One of the first typical technologies is search engines. For the bias that is generated by search engines, see Mowshowitz, Abbe, and Akira Kawaguchi. "Assessing bias in search engines." Information Processing & Management 38, no. 1 (2002): 141-156; Goldman, Eric. "Revisiting search engine bias." Wm. Mitchell L. Rev. 38 (2011): 96.

can determine how data is collected, coded and processed within a program.[611] An algorithmic system is a compound of editor selection and audience selection systems. In this regard, the results shown to consumers are not only determined by the data that is processed by them, but it also relies heavily on the behaviour of the platform. On the one hand, the result is influenced by the user profiling process, in which user profiles are collected and processed. From this perspective, the result that a platform shows to a user not only reflects his/her own preferences (e.g. based on the previous search keywords), but it also includes recommended results based on other users with similar preferences.[612] On the other hand, human factors play an essential role in the development of algorithmic systems. In this sense, like traditional intermediaries (e.g. media), platforms can control the diffusion of information via governing algorithmic systems.[613] In this regard, by adopting different algorithmic systems, the output generated by the same set of data can result in totally different outputs.[614]

From the perspective of product safety, consumers hope that platforms can correctly rank and filter the safe designs and services to them. However, this prospect is, in reality, not seen in every case. As mentioned above, the choice of the algorithmic system may be blurred by the various private interests of the platform as well as the historical data processed from the consumer side. Therefore, the information shown to consumers with the help of algorithmic systems is the content that the platform wants consumers to see. This indicates that the information disclosed via algorithmic-based systems could be inconsistent with the socially optimal outcome that we pursue.[615]

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[611] Cormen, Thomas H., Charles E. Leiserson, Ronald L. Rivest, and Clifford Stein. INTRODUCTION TO ALGORITHMS. MIT press, 2009.

[612] This is the so-called social information filtering process. See Garcia-Molina, Hector, Georgia Koutrika, and Aditya Parameswaran. "Information seeking: convergence of search, recommendations and advertising." Communications of the ACM (Accepted) (2011).

[613] See Bozdag, Engin. "Bias in algorithmic filtering and personalization." Ethics and information technology 15, no. 3 (2013): 209-227.

[614] This proposition on algorithm bias shows a sharp contrast with many previous kinds of literature, which assumed that platforms are neutral and objective and credible information would be revealed in the operation of these online intermediaries. See Bruns, Axel. "Gatewatching, Gatecrashing: Futures for Tactical News Media." In Megan Boler (ed.), DIGITAL MEDIA AND DEMOCRACY: TACTICS IN HARD TIMES, MIT Press, 2008, at 247.

[615] Friedman, Batya, and Helen Nissenbaum. "Bias in computer systems." ACM Transactions on Information Systems (TOIS) 14, no. 3 (1996): 330-347.

In reality, a couple of problems arise when there is a reliance on algorithms to disclose product risk.[616] One typical issue related to information disclosure is that the outcome of algorithms could be *biased*.[617] To explain, human manipulation is not only seen in the manual adjusting of the index processed by the system. It also determines what kind of data is included.[618] For example, websites like Google usually set up blacklisting and whitelisting to demote or promote a specific source of content.[619] Apart from human interventions, the limited size of the proxies chosen by the platform, as well as the amount of data collected by it, can lead to bias in the results shown to consumers.[620]

10.1.3. Regulatory interventions toward platform governance

The discussion so far has indicated that intermediary platforms may play a role in reducing accidents through various ways of governance strategies. However, as platforms design their

[616] For a general overview of the legal problems generated by applying algorithms, see Ghatnekar, Seema. "Injury by Algorithm." *Loy. LA Ent. L. Rev*. 33 (2012): 171.

[617] For a general study on bias in the age of information technology, see Sunstein, Cass R. REPUBLIC. COM. Princeton university press, 2001; Sunstein, Cass R. INFOTOPIA: HOW MANY MINDS PRODUCE KNOWLEDGE. Oxford University Press, 2006. For early discussions on the bias generated in computer systems, see Friedman and Nissenbaum (1996), supra note 615.

[618] Goldman, Eric. "Search engine bias and the demise of search engine utopianism." In Web Search, pp. 121-133. Springer, Berlin, Heidelberg, 2008.

[619] See Bozdag (2013), supra note 613, at 217.

[620] This is the so-called transparency problem with the application of algorithms. For a general discussion on this topic, see Desai, Deven R., and Joshua A. Kroll. "Trust but verify: A guide to algorithms and the law." *Harvard. J. L&T* 31:1 (2017); Chander, Anupam. "The racist algorithm." *Mich. L. Rev*. 115 (2016): 1023. For the possible measures to deal with ambiguous decision-making by algorithm, see Kleinberg, Jon, Jens Ludwig, Sendhil Mullainathan, and Cass R. Sunstein. "Discrimination in the Age of Algorithms." *NBER working paper series* (2019). In another paper, instead of focusing on consumer abilities to make informed choices about their personal data, an interaction between consumer protection authority and data protection authority is advocated. See Larsson, Stefan. "Algorithmic governance and the need for consumer empowerment in data-driven markets." *Internet Policy Review* 7, no. 2 (2018). Literature also indicates the importance of fostering collaboration across scholars and scientists in different sectors, including computer science, law and policy making. See Kroll, Joshua A., Solon Barocas, Edward W. Felten, Joel R. Reidenberg, David G. Robinson, and Harlan Yu. "Accountable algorithms." U. Pa. L. Rev. 165 (2016): 633. At the current stage, many online platforms are taking a role as a searching engine like Google. CAD files from various platforms can be accessed by users on such a single platform. For example, GrabCAD (See https://grabcad.com/library) claims that over 5,690,000 engineers and 3,430,000 free CAD files can be accessed. This implies that the extent to which the CAD files are ranked on this one-stop platform is of great importance. Literature also shows other problems caused by the biased algorithm process. For instance, by ranking and filtering the safety of the designs and products via algorithms, the individual producers who provide less safe products can be pushed out of the market indirectly. However, many other innocent parties can also be excluded in this course. See Karapapa, Stavroula, and Maurizio Borghi. "Search engine liability for autocomplete suggestions: personality, privacy and the power of the algorithm." *International Journal of Law and Information Technology* 23, no. 3 (2015): 261-289.

governance framework in accordance with their private interests, their operations may be inconsistent with the prevailing social interest. For example, it is observed that platforms are proactive to take measures under Model B.3. In comparison, under Model A.1, platform governance is designed in a way to accelerate innovation and the spread of CAD file designs. Under this background, additional instruments are needed to provide platforms with the incentive to improve their governance by taking various governance methods into consideration.

Authorities have recognised the increasingly important role of the platform in the digital age in recent years. Since 2016, a series of studies have been carried out by the EC to identify the challenges brought about by online platforms and, more importantly, to consider how to incentivise them to behave appropriately. The primary goal of these legal efforts is to make business fair and transparent in the age of the platform economy. In the current stage, multiple measures have been adopted to provide additional incentives to platforms to enhance their governance.

Improving the fairness and transparency of platforms

Firstly, in July 2019, Regulation (EU) 2019/1150 was issued by the EC (hereinafter the "*Platform Regulation*").[621] This regulation sets out to improve the fairness and transparency of online platforms.

The platforms targeted by the Platform Regulation include online e-commerce marketplaces, online software application services and online social media services. In this regard, a wide range of platforms fall into the scope of the Platform Regulation.[622] However, platforms without the presence of business users are excluded from the Platform Regulation.

According to the Platform Regulation, the operator of the platform shall set out in their terms and conditions the *main parameters* determining the ranking.[623] What is more, it has to explain why these main parameters are more important as opposed to other parameters, which may include any

[621] The REGULATION (EU) 2019/1150 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 20 June 2019 on promoting fairness and transparency for business users of online intermediation service. OJ L 186.

[622] For example, Amazon, Alibaba and eBay belong to the E-commerce marketplace. Google Play and Apple App Store are typical online software application services. The typical online social media services are Facebook and Instagram.

[623] See Article 5(1) of the Platform Regulation.

general criteria, processes and specific signals incorporated into the algorithms or any other adjustments used in connection with the ranking. Therefore, the platform does not need to explain in detail how the ranking algorithms work.[624]

In addition to complying with the transparency requirement on ranking, the platform shall include in their terms and conditions a description of any *differentiated treatment* in relation to the goods or services offered to consumers. Particularly, the platform shall explain the main economic, commercial and legal considerations for such differentiated treatment.[625]

However, from the viewpoint of positive legal analysis, this initiative may not perfectly fit with 3D printing. According to the legal text, the "online platform" defined in the *Platform Regulation* only refers to the online intermediary services that "allow business users to offer goods or services to consumers".[626] In this regard, while online marketplaces under Model A.2 and Model B.2 have to adjust their terms and conditions to comply with the transparency requirement, platforms that run a business on an open-source basis (i.e., Model A.1) are excluded from this regulatory regime.

The efforts to combat illegal online content

In addition to the *Platform Regulation*, measures have been proposed by the EC to deal with illegal online content (i.e., the "*Recommendation*").[627] Illegal content means "any information which is not in compliance with Union law or the law of a Member State concerned".[628] In this sense, no matter whether the CAD file is defined as a product or as digital information, the CAD file makers would be subject to the requirements suggested under the *Recommendation*. According to the *Recommendation*, the host service provider (i.e., the online platform) should diligently process the noticed content. If the content is found to be illegal, the host service provider should give notice

[624] See Article 5(6) of the Platform Regulation.

[625] See Article 7(1) of the Platform Regulation.

[626] Article 2 of the *Platform Regulation*.

[627] See the COMMISSION RECOMMENDATION of 1.3.2018 on measures to effectively tackle illegal content online. C(2018) 1177 final.

[628] See Article 4(b) of the *Recommendation*, supra note 627.

to the content provider to remove it.[629] The content provider has the right to contest the decision given by the platform. This "notice-and-takedown" system was suggested to be appropriate for online platforms.[630] At present, this mechanism is still in a non-binding form, so that online platforms are not forced to respect this *Recommendation*. In other words, it currently serves as a soft law proposed to enhance platform governance. It can be expected that if this *Recommendation* is formally recognised as a regulation that is implemented uniformly across the EU, online platforms that run 3D printing businesses will be subject to an intermediary liability if they fail to enforce the "notice-and-takedown" mechanism.

10.2. Risk-shifting via intermediary platforms

Besides improving the effect on deterrence, the platform could also take a role of helping to shift the risk in the context of 3D printing. Before examining the details of how platforms contribute to risk-shifting, it is of great importance to establish why platforms are willing to provide insurance for their users. The main goal of operating a platform is to maximise profits. In order to achieve this goal, a variety of measures are taken by the platform to attract more CAD file makers and fabricators to run their business on the platform and to increase the engagement of potential consumers. One crucial factor that determines whether a specific online platform possesses a comparative advantage over others is whether the CAD file or the fabricating service is safe. To explain, if the users feel that the CAD files or fabricating services are unsafe or that they have already been damaged by using a product, they will choose to stay away from this particular website and turn to other platforms with a guarantee of safety. Against this background, online platforms are motivated to provide additional guarantees to potential users.

The previous analysis indicates that, due to the issue of uninsurability, adverse selection and moral hazards, where producers and consumers can both spread the losses, first-party insurance is deemed to be a better method than third-party insurance for risk-shifting.[631] In the context of 3D

[629] See Article 5-8 of the *Recommendation*, supra note 627.

[630] See Article 9-13 of the *Recommendation*, supra note 627.

[631] See the discussion in Section 8.3 and Section 8.4.

printing, these problems deteriorate, especially under specific business models (e.g. Model A.1, Model A.2 and Model B.2).

In the scenario where the transaction takes place on an intermediary platform, a platform may engage in risk-shifting generally in two ways.[632] Firstly, the platform could help consumers to purchase coverage with every transaction. What is more, given the application of strict liability, CAD file makers and fabricators could rely on platforms to shift the risk. The analysis in this discussion shows that if CAD file makers and fabricators are subject to strict liability, the engagement of the platform in risk-shifting may considerably ease the difficulty of risk-shifting in the business models where liability insurance generates the most problems (e.g. Model A.1, Model A.2 and Model B.2). From this perspective, the difficulty of shifting risk may not be an argument against applying strict liability.

10.2.1. Platform insurance

Insurance is a crucial method of risk-shifting. This propostion does not change in the context of 3D printing. Given that strict liability applies to CAD file makers or fabricators, they might have a motive to shift the risk through liability insurance. However, according to the previous analysis, this does not ensure an increase in social welfare, since these parties may not be offered the coverage by insurers. Alternatively, when these parties are offered coverage, their incentive to behave appropriately may be distorted. The following analysis explains the extent to which platform insurance can be used to ease the barriers when CAD file makers and fabricators intend to shift the risk through liability insurance.

The definition of platform insurance

The first question to be asked is the role of the platform. In this sense, people may wonder whether the platform is an insurer that offers coverage to CAD file makers and fabricators, or whether it is a *broker or agent* to distribute insurance, or whether it simply serves as an *ancillary insurance intermediary* in cooperation with insurance brokers and agents. In theory, the platform may take

[632] See Lobel, Orly. “The law of the platform.” Minn. L. Rev. 101 (2016): 87.

on all of these roles. However, in reality, due to the limited capacity to bear the risk and the stringent requirement to apply for a license, an intermediary platform that is specialised in other primary activities may hardly engage in risk-shifting as an insurer. Therefore, a practical way for a platform to engage in risk-shifting is to act as a third party to cooperate with professional insurance brokers and agents. Alternatively, it can step forward and apply to become a distributor (e.g. insurance broker or agent).

If an intermediary platform decides to cooperate with professional insurance brokers or agents and serve as an ancillary insurance intermediary, it only needs to register with the competent authority of the Member State where it resides.[633] There is no necessity to apply for a license. In this situation, the insurance is complementary to a primary good or service, and the role of the platform is serving as an ancillary intermediary to provide insurance brokers or agents with a channel to sell their insurance products. According to the Directive (EU) 2016/97 on insurance distribution (hereinafter the "IDD")[634], if the premium does not exceed a certain amount and the risks covered are limited, the ancillary insurance intermediary would not be subject to IDD, which aims at regulating the activities of insurance distributor. In practice, ancillary insurance distributors normally do not substantially engage in business such as sales, underwriting, settlement of claim and post-sale service that can only be undertaken by insurance brokers or agents.

Apart from being an ancillary insurance intermediary, the platform may also choose to operate insurance distribution by registering either as an independent insurance broker representing the users of the platform or as an insurance agent acting in the name of specific insurance undertakings. If this is the case, normally the platform falls into the scope of insurance distributor and it has to meet a couple of requirements established by the domestic authorities such as respecting the rules of conduct, satisfying the minimum capital requirements, offering proof of qualifications and experience etc. These standards, however, could be substantially lower than the requirements for

[633] See Article 3 of Directive (EU) 2016/97 of the European Parliament and of the Council of 20 January 2016 on insurance distribution (recast)Text with EEA relevance OJ L 26, 2.2.2016.

[634] Directive (EU) 2016/97 of the European Parliament and of the Council of 20 January 2016 on insurance distribution (recast)Text with EEA relevance OJ L 26, 2.2.2016.

insurers. For instance, in many countries, the minimum capital requirement for insurance distributors equals to the minimum capital requirement for limited liability company.[635]

To summarise, in this research, the scope of *platform insurance* is limited to the case in which platform serves as an ancillary insurance intermediary in cooperation with registered insurance distributors, or it becomes an insurance broker or agent to digitally distribute liability insurance in a direct way to CAD file makers and fabricators.

The merits of platform insurance

As analysed, given that they are subject to strict liability, a substantial problem for CAD file makers and fabricators in relation to risk shifting is that they may not spread the risk over a considerable number of consumers. What is worse is that when they attempt to shift the risk through liability insurance, insurers might be reluctant to provide them with coverage. Worse still, even if these parties are insured, the increasing presence of adverse selection and moral hazard problems may induce them to behave inappropriately. The analysis in this subsection indicates that these problems could be alleviated by platform insurance.

On the one hand, platform insurance could reduce the problem of adverse selection. One obstacle confronted by insurers is that they may not have a sufficient number of profiles to differentiate the scale of risk borne by various CAD file makers or fabricators. As a result, they may mistakenly place parties with different risks into the same risk-pool and apply a similar premium to these parties. As a result, it is inevitable that some insured parties, which have a higher level of risk, are paid by some others that are with a lower level of risk. In contrast, an intermediary platform holds a great deal of data relating to the CAD file makers and fabricators who establish their business there. Such data is tailored to each user, ranging from the 3D printing method used by a fabricator to the scope of the service offered by a CAD file maker. Holding such information makes intermediary platforms advantageous to traditional insurers in terms of observing the risk of the insured parties, so that they seem to be a more suitable party to assess the risk of the insured

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[635] See for example, FSMA. "Obtaining a registration as an insurance intermediary in Belgium." 2019, available at: https://www.fsma.be/sites/default/files/public/content/EN/intermediairies/20180529_quickstartguide_obtainingalicenseasaninsurance.pdf.

parties.[636] Therefore, either organised in a way of cooperating with insurers or serving as an independent broker or agent, platform insurance would result in a better result of risk-differentiation. In consequence, homogenous CAD file makers and fabricators might be categorised into the same risk pool.

On the other hand, platform insurance has the potential to ease the moral hazard problem. One issue that prevents insurers from providing the injurers with liability insurance lies in the difficulty of monitoring the behaviour of the insured parties. As analysed, production in the context of 3D printing is organised in decentralised business models (e.g. Model A.1, Model A.2 and Model B.2). In these scenarios, as the CAD file makers and fabricators come from different corners of the world, it becomes challenging for traditional insurers to monitor the behaviour of these parties after concluding the insurance contract. This situation might be improved with the application of platform insurance. If a platform serves as the insurance broker or agent, it is reasonable to estimate that it could react faster than traditional insurers to monitor the insured parties. As a result, CAD file makers and fabricators are likely to take sufficient precautions even after being offered the coverage.

To conclude, platform insurance adds great value to risk management in the context of 3D printing. The platform as the party who is best positioned to observe the behaviour of the CAD file makers and fabricators. Therefore, from the perspective of risk-shifting, the application of platform insurance has the potential to reduce adverse selection and moral hazard problems. It is noted that platform insurance may incur other compliance issues. If a platform chooses to be an ancillary insurance intermediary, it might be out of the scope of IDD.[637] Also, as a data controller, the platform should also comply with data protection regulations, such as the General Data Protection Regulation (i.e. the "GDPR").[638]

[636] Eling, Martin, and Martin Lehmann. "The impact of digitalization on the insurance value chain and the insurability of risks." *The Geneva Papers on Risk and Insurance-Issues and Practice* 43, no. 3 (2018): 359-396.

[637] See Article 1(3) of the IDD.

[638] See Article 24 of the GDPR. Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC.

10.2.2. Platform as the governor of risk-sharing agreements

In reality, apart from liability insurance, injurers can shift risk through other methods. In theory, one of these alternative methods is a risk-spreading agreement, meaning that parties with identically valued risk agree to construct a risk pool, so that they can share the risk collectively.

In practice, the use of a risk-sharing agreement is observed in the sectors where risk on a large scale may hit a party, but this party may have no capacity to bear this risk independently.[639] Therefore, if several parties who bear the identical risk can reach an agreement, they together serve as a sort of alliance and are presumed to have a better ability to resist the risk. For example, risk-sharing agreements are applied by plant operators in response to a potential nuclear liability. Also, in the pharmaceutical industry, contractual agreements are established between the industrial actors to address the potential risk associated with drug innovation.[640] Sometimes, the agreement includes a wide range of stakeholders and institutional designs are needed.[641] In theory, a risk-sharing agreement is not constrained to the area where risk is on a large scale. Instead, a risk-sharing agreement can play a role as long as the certainty of risk is hard to estimate.[642]

The pros and cons of shifting risk through risk-sharing agreements

Compared to liability insurance, the importance of predictability declines as risk-sharing agreements are adopted.[643] In other words, so long as the parties understand that some risks would be presented to them, they can come up with an agreement together on risk distribution even if no statistical data or precise evaluation is available for prediction. This attribute of risk-sharing

[639] See Faure, Michael G., and Göran Skogh. "Compensation for damages caused by nuclear accidents: A convention as insurance." *Geneva Papers on Risk and Insurance. Issues and Practice* (1992): 499-513; see also Faure, Michael G., and Karine Fiore. "The coverage of the nuclear risk in Europe: Which alternative?" *The Geneva Papers on Risk and Insurance-Issues and Practice* 33, no. 2 (2008): 288-322.

[640] De Pouvourville, Gerard. "Risk-sharing agreements for innovative drugs." *European Journal of Health Economics*, (2006): 155-157.

[641] See Skogh, Göran. "Risk-sharing institutions for unpredictable losses." Journal of Institutional and Theoretical Economics (JITE)/Zeitschrift für die gesamte Staatswissenschaft (1999): 505-515; see also Faure and Hartlief (2003), supra note 496, at 163-67.

[642] See Faure and Hartlief (2003), supra note 496.

[643] See Faure and Hartlief (2003), supra note 496.

agreements determines that they could be advantageous for the risks relating to natural disasters or technological evolutions.[644] In both cases, no historical data or knowledge is available to predict the size of the risk in advance.

In addition, a risk-spreading agreement is considered to perform better than insurance in risk-differentiation and risk monitoring.[645] Compared to insurance, risk-differentiation no longer takes on the role of increasing predictability. Instead, it is of great importance in making clear the extent to which different parties will distribute the losses caused by them and the extent to which they will share the collective responsibility.[646] Assumptions are made that parties facing similar risks can identify each other and that they have the capacity to monitor each other after reaching an agreement.[647] In this regard, it is implied that only the parties with the incentive to shift similar risk will ultimately come to an agreement, while parties holding a different risk will be excluded.[648] As a result, the risk can be spread through mutual agreements in a spontaneous way.

Moreover, literature indicates that risk-sharing agreements may be cost-beneficial because the analysis of the actuarial information may not be necessary[649]. In this regard, parties can choose to share the risk either through an ex-ante or ex-post agreement.[650] The agreement thereby acts as a contract setting out the criteria for risk-sharing after the losses occur. The payment by the members is also not a sunk cost. Instead, the members will lose the payment only if an accident takes place.[651] Then, in this latter case, the members are incentivised to comply with the agreed terms.

Despite the advantages, the effect of risk-sharing agreements may also be diminished under several conditions.

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[644] Skogh, Göran, and Hong Wu. "The diversification theorem restated: Risk-pooling without assignment of probabilities." *Journal of Risk and Uncertainty* 31, no. 1 (2005): 35-51.

[645] See Faure and Fiore (2008), supra note 639.

[646] Faure, Michael G. "Alternative compensation mechanisms as remedies for uninsurability of liability." The Geneva Papers on Risk and Insurance. Issues and Practice 29, no. 3 (2004): 455-489.

[647] Skogh, Göran. "Development risks, strict liability, and the insurability of industrial hazards." *Geneva Papers on Risk and Insurance. Issues and Practice* (1998): 247-264.

[648] See Skogh (1999), supra note 641.

[649] See Faure and Hartlief (2003), supra note 496, at 167-68.

[650] See Faure and Hartlief (2003), supra note 496, at 168.

[651] See Faure and Fiore (2008), supra note 639.

Firstly, as we have identified, the risk-differentiation advantage of a risk-sharing agreement is based on the assumption that the involved members can identify each other. However, the extent to which parties with similar risks can successfully come to an agreement is mainly dependent on collective action. On the one hand, parties must have a common interest in collecting and sharing information with each other. This constitutes the basis for further allocating responsibilities. It is easier to reach an agreement in a situation where the parties come from a stable community and are familiar with each other than it is where the parties are strangers.[652] On the other hand, the transaction cost of this collective action must be considered. If the cost of the collective action to reach a risk-spreading agreement is high, insurance may still serve as a better mechanism, since the insurers may serve as a cost-effective way of coordinating various non-interactive parties and constructing a risk pool for them. Therefore, it is crucial to evaluate the cost of collective action before generalising a risk-sharing agreement. In addition to the cost of collective action, the operation cost of a risk-sharing agreement can also be high.[653] In order to ensure that the parties comply with the agreement, a *governance scheme* must be established alongside it.[654] One manager has to be appointed to govern the pool. This manager should not only be equipped with the capacity to monitor the risk that is posed by the members but s/he should also represent the interests of all members. If the cost of governance is taken into account, risk-spreading agreements may turn out to be a costly scheme for risk-shifting and compensation. As a result, risk bearers may not choose to use risk-spreading agreements to shift risk.

Secondly, the use of risk-sharing agreements is not immune to adverse selection and moral hazard.If information such as technical capacity and the adoption of standards is disclosed within the group and the group members reach a consensus to distribute the responsibility in accordance with appropriate criteria, then risk-spreading agreements can play a role in shifting risk.[655] However, where the criteria cannot be precisely perceived within the community, then the agreement may not be viable.[656]

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[652] See Skogh (1998), supra note 647.

[653] See Faure and Hartlief (2003), supra note 496, at168.

[654] Ibid.

[655] See Faure and Fiore (2008), supra note 639.

[656] In this case, the good risks are treated in no difference with the bad ones. Members with low risks will thereby pay the damage for the ones with high risks in the end.

Applying risk-sharing agreements in the context of 3D printing

Having analysed the theoretical implications of risk-sharing agreements, the question arises as to whether they are a promising complementary scheme of risk-shifting in the context of 3D printing.

The main obstacle to employing risk-sharing agreements lies in collective action. As we have identified, the basis for reaching a risk-sharing agreement is that multiple parties who bear similar risks are willing to manage the risks together. In other words, where various parties bearing similar risks cannot easily reach an agreement collectively, risk-sharing agreements may not be a suitable way of risk-shifting. In the context of 3D printing, different CAD file makers and fabricators are distributed around the world. The difficulty of reaching an agreement among a group of CAD file makers or fabricators comes from multiple aspects. Firstly, individual producers need to have a common objective of risk-shifting; this is the case only when risk-averse individual producers can be accurately distinguished from risk-neutral ones. Secondly, risk-averse individual producers need to have the chance to initiate an agreement collectively to tackle the uncertain product risk with 3D printing. Thirdly, in the context of 3D printing in a situation where the risk preference can be identified and collective action is possible, coordination may be perceived as another problem that prevents the realisation of a risk-spreading agreement. In this regard, a qualified party is necessary to coordinate the different voices and to form rules that are acceptable to the members.

Against this background, online platforms may play an important role in helping the isolated individual producers to reach a risk-spreading agreement. Firstly, as a great number of CAD file makers or fabricators aggregate and run their businesses on the intermediary platform, it offers a chance to constitute a large risk pool. Secondly, the platform may act as a suitable governor to coordinate the involved parties to reach an agreement. In this sense, by collecting data from its users in compliance with the relevant data protection laws, a platform may have a better chance of understanding the parties with risk-shifting demands and working out a risk-spreading scheme on behalf of these parties. Thirdly, the platform is a suitable party to enforce the agreement. In practice, the platform can collect the monetary contribution to the agreement flexibly. For example, in order to join the agreement, CAD file makers and fabricators may either be required to pay an ex-ante deposit or be asked to conclude a contract of promising to pay after damage is caused by them. If these parties refuse to respect the rule set by the agreement, the platform may take measures like suspending the user account.

The analysis above shows that in either liability insurance or risk-sharing agreement, adverse selection and moral hazard problems affect the effect of risk-shifting to a large extent. In recent years, platforms are embracing insurance technologies as their underlying architecture to improve their governance. In the next subsection, blockchain is used as a typical technology to explain this tendency, the main interest of which is to explore how such technologies are employed to increase the efficiency relating to risk-shifting.

10.2.3. Introducing blockchain technology as the architecture for platform governance

"Code is law". [657] This is what Professor Lessig articulated two decades ago in his monograph. In the digital age, not only are the interactions between people increasingly governed by cyberspace and the architecture behind it, but the software applied in cyberspace is showing a promising function in terms of stipulating what people can and cannot do.[658] In recent years, with the advances made in the Internet architecture, the behaviour of different parties can be constrained by technologies. In practice, a variety of technologies have been employed in response to this trend. For example, the digital rights management system (DRM), by transforming copyright rules into technical measures, is designed to protect copyright when works are uploaded and disseminated online.

In the context of 3D printing, disruptive technologies also take a role in incentivising the relevant parties to behave appropriately. The discussion below uses emerging blockchain technology as an example to show how platforms can build safe ecosystems with the help of this disruptive technology.

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[657] Lessig, Lawrence, CODE: AND OTHER LAWS OF CYBERSPACE. Basic Books, 2009.

[658] As Lessig articulated in his book, "we can build, or architect, or code cyberspace to protect values that we believe are fundamental, or we can build, or architect, or code cyberspace to allow those values to disappear." See Lessig (2009), supra note 657, at 6.

The value added by blockchain technology

Blockchain technology is a protocol for the exchange of data over the Internet.[659] Unlike traditional methods where information is stored and updated by a central ledger (e.g. insurer), every player in the blockchain serves as a node that can store the information of the whole network. Therefore, every party within the network is essentially a database that can store and update all the information. This key feature makes blockchain a promising technology in the context where a party intends to access credible information from a great number of other parties who are decentralised.[660]

Compared to traditional ways of storing data, blockchain has several unique features.[661] Firstly, whenever a party on the blockchain changes or updates information, all of the other actors throughout the whole network are informed. In other words, a party cannot hide any information. Secondly, once the information is updated to all members on the network, it is impossible to withdraw this action. In this regard, data is immutable over the network. Thirdly, all of the data is traceable. This implies that all of the historical information relating to a specific party can be identified.

Blockchain technology: providing parties with the incentive to behave appropriately

The technological characteristics of blockchain have considerable implications when tackling information asymmetry.[662]

In the traditional context, credit is determined by a central agent (e.g. the insurer). The extent to which such an agent is able to understand a risk correctly is largely dependent on its capacity to

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[659] Swan, Melanie. BLOCKCHAIN: BLUEPRINT FOR A NEW ECONOMY. O'Reilly Media, Inc., 2015.

[660] Applying in the decentralized context constitutes as the main difference between blockchain technology and other mechanisms in terms of accessing information. A decentralized context, defined by Benkler, refers to the conditions "conditions under which the actions of many agents cohere, and are effective despite the fact that they do not rely on reducing the number of people whose will counts to direct effective action." Benkler, Yochai. THE WEALTH OF NETWORKS: HOW SOCIAL PRODUCTION TRANSFORMS MARKETS AND FREEDOM. Yale University Press, 2006, at 62.

[661] See Swan (2015), supra note 659.

[662] Cong, Lin William, and Zhiguo He. "Blockchain disruption and smart contracts." No. w24399. National Bureau of Economic Research (NBER), 2018.

access and assess the relevant information. However, a central agent may misunderstand the risk and accordingly make a bad decision.[663]

In contrast to the conventional picture, blockchain is considered to reduce the information asymmetry among the members within the network.[664] With the use of blockchain technology, information is no longer censored by a central agent. Instead, any private information is stored and updated across the whole network. It is therefore impossible for an actor to conceal relevant information unless it is agreed by at least half of the members, which is highly unlikely.[665]

Blockchain technology also promises a reconstruction of the credit system. Blockchain technology in origin is a way of protecting information. It draws on the science of cryptography which focuses on using protocols to govern transactions.[666] If a block is added in an attempt to cheat the system, it will be identified by the other parties. Without the consensus of the other parties, malicious information will not be accepted by the network. At present, blockchain technology is a credible mechanism that has been adopted in many different sectors. For example, in the financial sector, money can be transferred without the endorsement of banks.[667] Similarly, blockchain technology can also be used to certify the copyright of a work.[668] In both cases, a credible intermediary (i.e. bank and intellectual property) is no longer needed with the application of blockchain technology.

In addition to solving the credibility of the data, introducing blockchain technology also has a crucial implication for data protection and cybersecurity. With blockchain, all of the data is fully encrypted. The public-private key cryptography ensures that only the intended recipient can access

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[663] See Fulmer, Nathan. "Exploring the Legal Issues of Blockchain Applications." *Akron L. Rev*. 52 (2018): 161.

[664] Szczerbowski, Jakub J. "Transaction Costs of Blockchain Smart Contracts." *Law and Forensic Science* 16 (2018): 2.

[665] Lemieux, Victoria Louise. "Trusting records: is Blockchain technology the answer?" *Records Management Journal* 26, no. 2 (2016): 110-139.

[666] Pilkington, Marc. "Blockchain technology: principles and applications." In F. Xavier Olleros, Majlinda Zhegu (eds.) RESEARCH HANDBOOK ON DIGITAL TRANSFORMATIONS. Edward Elgar Publishing. 2016.

[667] Guo, Ye, and Chen Liang. "Blockchain application and outlook in the banking industry." *Financial Innovation* 2, no. 1 (2016): 24.

[668] Savelyev, Alexander. "Copyright in the blockchain era: promises and challenges." *Computer law & security review* 34, no. 3 (2018): 550-561. The application of blockchain technology to certify and protect copyright is also widely discussed in the context of 3D printing. See Holland, Martin, Christopher Nigischer, Josip Stjepandić, and C. H. Chen. "Copyright protection in additive manufacturing with blockchain approach." Transdisciplinary Engineering: A Paradigm Shift 5 (2017): 914-921.

the data.[669] Therefore, compared with other architectures, blockchain promotes the protection of privacy. In addition, as the data is decentralised to many nodes, a cyberattack on a central server is no longer possible.

The value added by blockchain technology to risk-shifting in 3D printing

The features of blockchain technology have crucial implications for 3D printing. In the context of 3D printing, the application of blockchain technology is closely related to the platform. Provided that the platform adopts a blockchain architecture, then all the activities relating to parties will be recorded on the network irreversibly. In this sense, the chain that records the activities of the relevant parties would be a credible source for the platform when it is evaluating the risks posed by the existing members.

In particular, the application of blockchain technology not only fosters risk-differentiation ex-ante but also enables the behaviour of CAD file makers and fabricators to be monitored ex-post. Furthermore, key information that cannot easily be observed in a traditional context can be disclosed with the adoption of blockchain technology. The typical information is:

- *How many CAD files have been designed or remixed by a CAD file maker?*
- *How many final objects have been fabricated by a fabricator?*
- *What are the CAD files and products used for?*
- *Have some of these CAD files or products been reported as dangerous?*
- *In which countries were the CAD files of a party downloaded?*

The access to this information is crucial to platform insurance, since the platform can improve its understanding of the heterogeneity of its members. The CAD file makers and fabricators with the highest risk can be distinguished from those that are less risky. As a consequence, if the platform serves as an independent insurance broker or agent, the application of blockchain technology

[669] Kshetri, Nir. "Blockchain's roles in strengthening cybersecurity and protecting privacy." *Telecommunications policy* 41, no. 10 (2017): 1027-1038.

would help it to narrow down the risk-pools so as to apply insurance products precisely. In another case, if the platform as a third-party offers a distribution channel to insurance brokers and agents, given the compliance with data protection, by sharing data with insurance distributors, the platform also helps them to reduce the risk of adverse selection. In addition, in either case aforementioned, the platform is able to monitor the behaviour of its users in a timely manner. If a CAD file maker causes damage, it will be immediately reported across the platform, after which the platform could take measures to suspend or remove the risky CAD file or fabricating service before it results in more damage. This information possessed by the platform with the application of blockchain can also help the platform and insurance distributors to adjust the premiums in line with a changing level of risk and update the clauses of the insurance contract accordingly.

In short, by embedding blockchain technology into the platform, it is the technologies instead of the people or entities that take on the role of detecting information. Disclosing information in this way not only provides the relevant governors (e.g. the platform and insurer) with a better capacity to assess the risk posed by the CAD file makers and fabricators in a decentralised environment, but it also serves as an incentive to remind these parties that they should behave appropriately. Blockchain is therefore expected to be the technology that can make deterrence and risk-shifting more effective. At present, the potential of blockchain technology has not been fully discovered in the sector of insurance.[670] However, as blockchain technologies continue to develop, the value they could add to the insurance sector would massively exceed the cost. As a result, it is estimated that the insurance industry will swiftly embrace blockchain technology within the next few years.[671]

[670] Gilbert, S. "The Hype Cycle of Insurance Disruption." (2016). Available at: http://insurancethoughtleadership.com/the-hype-cycle-of-insurance-disruption/. Visited on October 10th 2018.

[671] McKinsey & Company. "Blockchain in Insurance: Opportunity or Threat?" Available at: https://www.mckinsey.com/~/media/McKinsey/Industries/Financial%20Services/Our%20Insights/Blockchain%20in%20insurance%20opportunity%20or%20threat/Blockchain-in-insurance-opportunity-or-threat.ashx. Visited on October 10th 2018.

10.3. Chapter conclusion

In brief, the analysis in this chapter implies that, when production is organised in a decentralised way under the separation models (especially under Model A.1, Model A.2 and Model B.2), the intermediary platform seems to be the more suitable party to observe the behaviour of CAD file makers and fabricators. Governance by the platform has the potential to improve the effect on deterrence and risk-shifting.

Platform governance is expected to improve the effect on deterrence from two aspects. On the one hand, by setting up entry requirements and codes of conduct, the platform provides relevant CAD file makers and fabricators with an incentive to take measure to reduce accidents. On the other hand, consumers could be linked with safe CAD files or printing services, given that platforms can categorise the information therein reasonably, that they can operate the rating system correctly, and that they can develop transparent filtering systems. The analysis also implies that platform governance is largely influenced by the private interest of the platform. If one platform adopts a higher standard of governance relating to product safety, but its competitor adopts a lower threshold, CAD file makers and fabricators may shift to running their businesses on this latter alternative platform. In this sense, platform governance should be offered extra incentives to behave in accordance with the socially optimal outcome. Otherwise, if an additional investment in improving the platform governance is not rewarded but simply results in an inferior status of its ability to engage the competition, platforms would have no motive to do so. In recent years, various regulatory instruments have been established to intervene in the governance of platforms. These measures are expected to improve the deterrence effect in an indirect way via platforms.

Platforms could also smooth the procedure of risk-shifting. This is not only reflected in a way that platforms could provide consumers with a channel to reach out to various first-party insurance products, but also more importantly, they help CAD file makers and fabricators to spread the risk given that these parties are subject to strict liability. Firstly, the platform might smooth the procedure of purchasing liability insurance. On the one hand, the platform may serve as an ancillary insurance intermediary to link CAD file makers and fabricators with liability insurance providers; on the other hand, the platform itself may apply for a license as an insurance distributor. Apart from liability insurance, risk-spreading agreements are also a way that platforms can engage in improving risk-shifting.

At last, the discussion in this chapter indicates the recent trend of employing disruptive technologies to smooth risk-shifting. In this sense, the adoption of blockchain technologies has the potential to differentiate risks and to monitor the insured parties.

Conclusions

Having analysed the performance of contract and tort liability respectively in Parts II and III, Part IV continues to explore whether complementary instruments could be introduced to improve deterrence and to help risk-bearers to shift the risk that they may have to bear. The role of regulators and platforms turns to be increasingly important. Various forms of regulations are considered to provide parties with an extra incentive to take precautionary measures or to disclose critical information. In addition, platforms might not only serve as a more suitable party to provide CAD file makers and fabricators with the incentive to behave appropriately, but they also act as an ancillary intermediary or a distributor to reduce the barriers of risk-shifting. The contribution of the platform is more important to the scenarios where production is decentralised. These scenarios, such as Model A.1, Model A.2 and Model B.2, are also the cases where contracts and tort liability fail to result in the socially optimal outcome.

CONCLUSIONS AND FINAL REMARKS

1. Answering research questions and presenting findings

This research examined the approach for dealing with product risk in the context of 3D printing. At the beginning of this research, four questions were asked. This part will answer these questions in sequence and summarise the main findings from the previous analysis.

1.1. The answer to Question 1

To what extent is 3D printing as a way of production different from traditional mass production, and what do these disruptions mean for product safety?

According to the analysis in Part I, the way in which 3D printing captures the value in the sector of production is quite different from traditional mass production. In general, 3D printing disrupts traditional mass production in four aspects. Firstly, complexity is reduced with the adoption of 3D printing. Secondly, economies of scale no longer serve as the threshold for parties intending to engage in production activities. Thirdly, the whole production process is divided into two separate parts: digital designing and physical fabrication, which increases the agility of production. Last but not least, the consumer plays a role in coordinating the production.[672]

In order to capture the value created by 3D printing, various practical business models are established. One is the so-called "one-stop" business model. This model shows few differences from traditional mass production, because all relevant activities are accomplished within one entity.[673] In many other cases, a consumer may choose to acquire the CAD file from one party and then turn to a separate printing service (i.e. the "separation" business model). It is this latter business model that leads to some new features regarding product risk.[674] Firstly, product risks increasingly stem from customised activities as opposed to mass production. Secondly, non-professionals are engaging in substantive activities intensively due to the removal of scale economies. Thirdly, coordination problems arise, because digital designing activities and physical

[672] See the discussion in Section 3.1.2 of Chapter 3.

[673] See the discussion in Section 3.2.1 of Chapter 3.

[674] See the discussion in Section 3.2.2 of Chapter 3.

fabrications are separately accomplished by the parties from different entities. Fourthly, consumers serve as the coordinator to proceed with the process of production.

In practice, considering the abovementioned features, business models relating to digital designing and physical fabrication could be largely different.[675] For example, a consumer may obtain a CAD file from different sources such as the open-source community (Model A.1), online platforms (Model A.2), or professional designers (Model A.3). Correspondingly, they can reach out to a printer from various service providers such as professional designers (Model B.1), online platforms (Model B.2) or agent platforms (Model B.3). This divergence indicates that consumers may have various channels for obtaining the final product. More importantly, it implies that, for specific parties to behave appropriately and to spread the losses, the instrument applied under different business models might be quite different.[676]

1.2. The answer to Question 2

To what extent can contractual parties reach an agreement to efficiently reduce accidents and to spread losses over contractual parties?

In order to achieve the socially optimal outcome, specific instruments should be applied to provide the relevant parties with the incentive to behave appropriately and to spread the losses when necessary. The discussion starts with the scenario in which parties can *bargain* with each other and explained why people could optimise their behaviours through bargaining in theory, given that several assumptions are satisfied.[677] However, a key challenge with this aspect is that bargaining over the allocation of production risk could be inefficient, due to the existence of prohibitive transaction costs and information problems.[678]

Whenever production is organised in a way that digital designing and physical fabrication are accomplished respectively by the parties from different entities, the consumer being the coordinator of the production process has to reach out to each of them for the sake of allocating

[675] See the discussion in Section 3.3 of Chapter 3.

[676] See conclusions of Part I.

[677] See the discussion in Section 4.1 of Chapter 4.

[678] See the discussion in Section 4.2 of Chapter 4.

the risk. However, as the analysis in Chapter 5 revealed, the efficiency of contracting over product risk could be divergent under various business models.

From the perspective of deterrence, the study found that if a consumer acquires a CAD file from a professional designer (e.g. under Model A.3) and then turns to a professional fabricator (e.g. under Model B.1 and Model B.3), contracting over product risk might provide CAD file designers with a decent incentive to behave appropriately.[679] In comparison, if a consumer acquires a CAD file from an open-source platform (i.e. under Model A.1) or an online marketplace (i.e. under Model A.2) and then takes the CAD file to a non-professional (i.e. under Model B.2), the consumer might turn out to bear more risk than expected.[680] It is noted that, due to the existence of information asymmetry, contractual parties can only be incentivised to optimise their behaviours to the extent that can be observed by the opposite party.[681] Therefore, we may expect an excessive level of activities when parties are subject to contractual liabilities.

From the perspective of risk-spreading, without additional instruments, contractual parties might not spread the losses efficiently in the context of 3D printing. In cases where CAD file makers and fabricators are non-professionals, they are often reluctant to bear the risk in advance, because these parties are not significantly less risk-averse than consumers.[682] Therefore, whenever production is organised under 3D printing, additional risk-shifting instruments should be provided to contractual parties.

1.3. The answer to Question 3

To what extent can tort liability rules incentivise parties to behave appropriately and help risk-averse parties to shift risk?

In the production sector, product liability is widely regarded as a critical instrument to deal with potential accidents. In the aftermath of the Industrial Revolution, the regime of strict product

[679] See the discussion in Section 5.1.3, Section 5.2.1 and Section 5.2.3 of Chapter 5.

[680] See the discussion in Section 5.1.1, Section 5.1.2 and Section 5.2.2 of Chapter 5.

[681] See the discussion in Section 5.3 of Chapter 5.

[682] See the discussion in Section 5.2 of Chapter 5.

liability was gradually established around the world; making producers liable, if damages are caused by their defective products.[683]

In recent years, the production sector has been witnessing several remarkable disruptions.[684] Firstly, production is not necessarily organised in an industrial way. Instead, a growing number of SMEs and individuals are engaging in production activities. Secondly, final products are increasingly obtained from the service context. Thirdly, the trend of digitalisation heavily influences the way of production as well as the function and performance of the final product. The changes noted above have generated enormous controversies as to whether product liability should be extended to these new contexts. More specifically, in the context of 3D printing, a practical issue being asked is: whether CAD file makers or fabricators should be subject to strict liability or fault-based rules? According to the positive legal analysis in Chapter 6, there is a great divergence across EU Member States. While some countries extend strict product liability to the new contexts, many countries still adopt contractual liability or fault-based rules.[685]

The law and economics analysis in Chapter 7 and Chapter 8 reveal contradictory stances on the practical aspects of expanding strict liability to CAD file makers and/or fabricators. The justifications in favour of applying strict liability to producer in traditional mass production cannot be observed when production is organised under separation models, where production is separately undertaken by the CAD file designer and fabricator.

Firstly, under separation models, it is hard to identify a party who is the most suitable to reduce accidents.[686] Under traditional production, the performance and function of products are substantially determined within the production process. This process is handled by producers, while consumers are not involved. Therefore, as the behaviour of producers is far more crucial than consumers, providing them with an incentive to behave appropriately would result in a higher level of social welfare than providing such an incentive to consumers.[687] However, this prospect

[683] See the discussion in Section 6.1. and Section 6.2 of Chapter 6.

[684] See the discussion in Section 6.3 of Chapter 6.

[685] See the discussion in Section 6.4 of Chapter 6.

[686] See the discussion in Section 7.1 of Chapter 7.

[687] See the discussion in Section 7.1.2 of Chapter 7.

is largely blurred in the context of 3D printing. Under separation models, as consumers serve as the coordinator of production, their activities are increasingly crucial to the accident cost. Therefore, it is not obvious which party serves as the most suitable one, who can reduce accidents at a lower price.[688]

Secondly, even if CAD file makers and/or fabricators are subject to strict liability, the full price might not be accurately perceived by consumers.[689] Under traditional mass production, the producer is considered to be better positioned to observe product risks. By imposing strict liability on producers, the full cost of a product is expected to be shown via the market price. As a result, consumers can make decisions efficiently.[690] However, when production is separately undertaken by CAD file makers and fabricators who are strangers to each other, it is unclear which party has the best information to evaluate the full cost of the whole production. Given strict liability, either the CAD file maker or the fabricator may have a good understanding of the cost generated by their own activities, but they may not precisely assess the cost arising from the other party. Therefore, applying strict liability to either CAD file makers or fabricators may not guarantee that consumers can perceive the full cost of the product accurately.[691]

Thirdly, in the context of 3D printing, applying strict liability might lead to considerable risk-spreading problems.[692] Unlike traditional mass production, where producers seem to be more capable of spreading product risk, under 3D printing CAD file makers and fabricators are usually SMEs or even ordinary individuals. Therefore, they tend to be more risk-averse than imagined. Provided that they are subject to strict liability, these parties have an incentive to purchase liability insurance to shift the risk of being liable to the damage caused by their defective products. This research shows that uninsurability problems prior to concluding the insurance contract as well as adverse selection and moral hazard problems after being insured would distort social welfare.[693] This distortion could be even worse when CAD file makers and fabricators are insolvent, which

[688] See the discussion in Section 7.1.3 of Chapter 7.

[689] See the discussion in Section 7.2 of Chapter 7.

[690] See the discussion in Section 7.2.1 of Chapter 7.

[691] See the discussion in Section 7.2.2 of Chapter 7.

[692] See the discussion in Chapter 8.

[693] See the discussion in Section 8.3 and 8.4 of Chapter 8.

in practice is very likely the case in the context of 3D printing.[694] The risk-shifting problems encountered in the application of strict liability again indicates that when both parties are able to shift risk, the first-party insurance accessed by consumers seems to be more efficient than the liability insurance available to producers.

Based on the law and economics analysis, imposing strict liability on CAD file makers and/or fabricators does not ensure a better deterrence and risk-shifting effect compared to fault-based rules. This conclusion is particularly relevant for countries seeking to adopt strict liability to achieve the goal of deterrence and risk-shifting.

When tort liability applies to accidents, courts are responsible for deciding the case. A considerable amount of research in law and economics has indicated that the errors made by courts would incentivise parties to behave inappropriately.[695] In the context of 3D printing, there is a large chance that courts may err in finding the level of care and the scope of liability (i.e. causation). From this perspective, the deterrence effect offered by tort liability might be distorted.[696]

1.4. The answer to Question 4

How can regulators and platforms take measures to improve the effect on deterrence and risk-spreading?

Besides market-based mechanisms, this research also explained how regulations and platform governance could play a role in improving the effect on deterrence and risk-shifting.

This research found that some regulations employed to intervene in contracting over product risk between producers and consumers in the context of traditional production still apply to CAD file makers and fabricators.[697] In specific terms, these parties are, firstly, required to offer legal warranties in the contract. In addition, these parties are required to disclose critical information to consumers. The application of mandatory standards and information regulations are expected to

[694] See the discussion in Section 8.4.2 of Chapter 8.

[695] See the discussion in Section 7.3.1, Section 7.3.2 and Section 7.3.3 of Chapter 7.

[696] See the discussion in Section 7.3.5 of Chapter 7.

[697] See the discussion in Section 9.2 of Chapter 9.

directly provide CAD file makers and fabricators with an incentive to take due precautionary measures.[698] With particular regard to business models where contract relations fail (e.g. in Model A.1, Model A.2 and Model B.2), the implementation of various regulations is of great importance. As for the form of regulations in the context of 3D printing, information regulations should be further encouraged. In comparison, due to the prohibitive administrative cost and the inclination to impede innovation, the scope of mandatory standard and prior approval should be carefully restricted. Prior approval should only be applied in limited areas, such as medical devices or food, where product risk could create hazardous outcomes.

Apart from regulation, platform governance is perceived as a crucially complementary instrument to improve deterrence. The analysis in this research has shown that intermediary platforms can influence the deterrence effect in two ways. Firstly, platforms may set up entry requirements and codes of conduct to induce actors to improve their activities.[699] Secondly, platforms may improve information disclosure through various mechanisms such as categorisation, rating and ranking.[700] However, as discussed in this research, platform governance is, at present, primarily driven by private interest. If a platform adopts a set of stringent entry requirements and codes of conduct, CAD file makers and fabricators might shift to other alternative platforms. Therefore, the fact that improving platform governance might not be rewarded with an increase in business success may preclude platforms from adopting correct governance strategies to reduce product risk. This research further argued that recent EU Directives and Regulations in this area would be helpful in encouraging platforms to improve their governance architecture.[701] By holding platforms liable under specific conditions and requiring them to comply with the rules on transparency, platforms are provided with an incentive to improve platform governance. Ultimately, not only would CAD file makers and fabricators be indirectly induced to behave appropriately, but consumers will also be able to assess product risk with more information.

Lastly, intermediary platforms are considered to improve the effect of risk-shifting. In this sense, intermediary platforms not only offer a channel to link consumers with the providers of first-party

[698] See the discussion in Section 9.3 of Chapter 9.

[699] See the discussion in Section 10.1.1 of Chapter 10.

[700] See the discussion in Section 10.1.2 of Chapter 10.

[701] See the discussion in Section 10.1.3 of Chapter 10.

insurance, but more importantly they help to reduce relevant problems when risk is spread under liability insurance.[702] For the latter proposition, this research proposed that platform serving as the party to better observe the behaviour of CAD file makers and fabricators can help to reduce adverse selection and moral hazard problems.[703]

2. Policy recommendations

The discussion in this research has shown a different landscape of production that is driven by 3D printing. In particular, when production is organised in a way that the entire process is coordinated by consumers, which is separately accomplished by CAD file makers and fabricators who are strangers to each other, it challenges the method that is traditionally employed to achieve socially optimal outcomes. Having analysed the efficiency of different instruments for reducing accidents and spreading losses, it is clear that socially optimal outcomes cannot be achieved through a single instrument. Instead, there is a need to apply different instruments smartly, in accordance with the concrete business models. Based on the law and economics analysis, some policy recommendations are proposed in the following parts.

2.1. Policy recommendations with respect to deterrence

The primary goal to deal with the accident within production sector is deterrence, which means that parties relating to accidents shall be provided with an incentive to optimise their behaviours. When production is organised separately and the business models used for digital designing and physical fabrication are in considerable divergence, different instruments shall be developed.

The first policy recommendation on deterrence is that parties, who engage in highly cooperative business models (e.g. Model A.3, Model B.1 and Model B.3) should be encouraged to deal with product risk through contractual relations. In this cases, as relevant digital modelling and physical fabrication activities are accomplished on a customised basis or in service contexts, their choices and preferences should be respected with restrictions imposed on the intervention of legal

[702] See the discussion in Section 10.2.1 of Chapter 10.

[703] See the discussion in Section 10.2.3 of Chapter 10.

instruments. In these contexts, legal interventions should aim at offering contractual parties with information to help them make decisions efficiently.

The second recommendation on deterrence is that legislators should be cautious about extending strict liability to the context of 3D printing. The analysis in this research revealed that the justifications for strict product liability in traditional production are not obvious in 3D printing. While it may incentivise CAD file makers and fabricators to take a higher level of precaution, the cost generated by strict liability could also be very high. This is observed especially in light of innovation obstacles and the problems generated in shifting liability risk.

The third recommendation on deterrence is to provide courts with reliable signals to reduce court errors. As the research has shown, courts could reach erroneous conclusions when applying liability rules. More specifically, they could incorrectly decide the scope of liability (i.e. causation) and misunderstand the due care level. This fact, on the one hand, requires courts to increase their ability to precisely decide relevant cases. On the other hand, authorities should make efforts to offer guidance on the assessment of the optimal level of precautions.

Last but not least, regulations and platform governance will play an increasingly important role with respect to deterrence. The analysis in this research indicated that these instruments would provide CAD file makers and fabricators with extra incentives to behave appropriately, especially under the business models where traditional legal instruments turn to be a failure (e.g. Model A.1, Model A.2 and Model B.2). In practice, regulators should continue to focus on the issue of regulating platforms. Specific regulations on categorising, ranking, rating system, as well as other mechanisms adopted in the environment of platform economy should be established.

2.2. Policy recommendations with respect to risk-shifting

When both parties have access to risk-shifting instruments to spread losses, traditionally, first-party insurance is considered to be a better policy than liability insurance. The reasons can be explained in three aspects. Firstly, shifting risk through liability insurance leads to distributive and deterrence distortions toward consumers. Secondly, the fact that risk becomes less predictable to insurers might lead to uninsurability problems. Thirdly, after concluding the insurance contract, adverse selection and moral hazard problems might distort the incentive offered to the insured parties. The analysis in this research has shown that the aforementioned problems still exist and might be even worse in the context of 3D printing. This observation, together with other propositions, inform the conclusion that extending strict liability toward CAD file makers and fabricators should be discouraged.

Therefore, the first policy implication is that first-party insurance is still the primary and desirable method for risk-spreading. The discussion in this research indicated that various platforms as the ancillary insurance intermediaries are playing an increasingly important role in the context of 3D printing.[704]

Further, in 3D printing contexts, since SMEs and ordinary individuals account for the majority of CAD files and fabricators, these parties are not significantly less risk-averse than consumers. Therefore, they may be unwilling to offer a warranty voluntarily. In practice, legal warranties are generally required, which will not only take a function of deterrence but also serve as a method to shift risk from consumers to producers. It should be noted that, considering the heterogeneity of consumers and the resulting adverse selection problems, this legal intervention should be limited and not fixed for a long time.

In practice, the EU is witnessing a large divergence in the form of liability imposed on CAD file makers and fabricators; some Member States are inclined to adopt fault-based rules, while others are prepared to extend strict product liability to CAD file makers and fabricators. Therefore, it could be expected that, in the near future, strict liability and fault-based liability would coexist at the domestic level. In this regard, while first-party insurance is deemed as a preferable way of risk-shifting, the quest for shifting liability risk is also increasingly important in the context of 3D printing. Some recommendations on this procedure are thus reflected as follows.

Firstly, legislators should work on reducing legal uncertainties that prevent insurers from predicting the legal risk accurately in the context of 3D printing. In particular, they should ensure that the form of liability is without ambiguity within one jurisdiction.[705]

Secondly, platforms are expected to play a crucial role in smoothing the process of risk-shifting. As a party that has a better ability than others to observe the behaviour of CAD file makers and

[704] See the discussion in Section 10.2.1.

[705] See the discussion in Section 8.3.1.

fabricators, the platform could help to improve differentiating risk or monitoring these parties either as an ancillary insurance intermediary or an independent insurance distributor. Hence, the policy implication at this point is two twofold. On the one hand, regulations should be adopted to encourage platforms to engage in the risk-shifting process. On the other hand, as the insurance distributor or ancillary insurance intermediary, platforms should comply with the rules on insurance distribution. Importantly, there is a pressing need to set up rules specifically on digital insurance distribution.

3. Limitations and further research

The adoption of 3D printing has dramatically transformed the traditional way of production, which not only creates value but also generates product risk and accidents. Therefore, legal instruments should be formulated to deal with product risk. This research applies the methodology of law and economics and chooses social welfare as the criteria to study what the legal regime toward 3D printing should look like. Following this thread, the primary goal of legal instruments is to provide relevant parties with the incentive to behave optimally. In addition, spreading risks resulting from accidents are also of great importance.

This research has assessed the current legal framework to understand whether it can achieve the goal of deterrence and risk-spreading. In general, the desirable legal framework for 3D printing context should be the one that can maximise social welfare. In this regard, this research does not touch upon the issue of *compensation*. Whether the injured party can be sufficiently compensated thereby is not considered. In reality, besides reducing accidents, compensating injured parties is also critical, especially when the injurer does not have sufficient assets. As analysed in this thesis, the judgement-proof problem might be frequently observed in the context of 3D printing, as CAD file makers and fabricators running relevant businesses are largely SMEs and individuals. Thus, further research should be conducted to study the compensation mechanisms that are available in the context of 3D printing.

Whenever production is organised in a way that consumers coordinate the separate digital designing and physical fabrication process, consumers themselves have a significant impact on accident costs. Hence, optimising the behaviour of consumers turns out to be an important issue in the context of 3D printing. Generally, the issues analysed in this thesis have some instrumental implications. For example, the arising important role of consumers is utilised to argue against extending strict product liability to CAD file makers and fabricators. Following this direction, further research should pay closer attention into how instruments can be specifically used to optimise the behaviour of consumers.

As the whole production process is respectively undertaken by differing entities, information is identified as an obstacle to prevent consumers from making efficient decisions. As market price is no longer a precise mechanism to help consumers perceive the full cost of the final product, consumers have to rely on other signals to make their evaluations. The analysis in this thesis has shown that a variety of instruments, ranging from mandatory standards issued by regulators to ranking algorithms running by platforms, could be used to provide consumers with more information to make decisions. Some other vital signals like reputation have proven to improve consumers' decision-making substantially. However, as the commercial use of 3D printing for production is relatively recent, it might take some time to fully assess the function of reputation in 3D printing. Further research on this topic is thus necessary.

For the sake of conducting the positive legal analysis and outlining the divergence among Member States, this thesis refers a wide range of literature including EU and national legislations as well as the most recent reports that can be accessible. However, this thesis still limits itself with regard to following the up-to-date legislative actions in certain Member States. The possibility of further discussions and reforms in Member States could be explored and updated in the future research.

Last but not least, the preliminary conclusions drawn from this thesis are based on the theoretical analysis. However, the extent to which these propositions are precisely observed in reality should be empirically examined. To have a better understanding, further research should design experiments or collect data to assess some of the key issues discussed in this thesis.

APPENDIXES

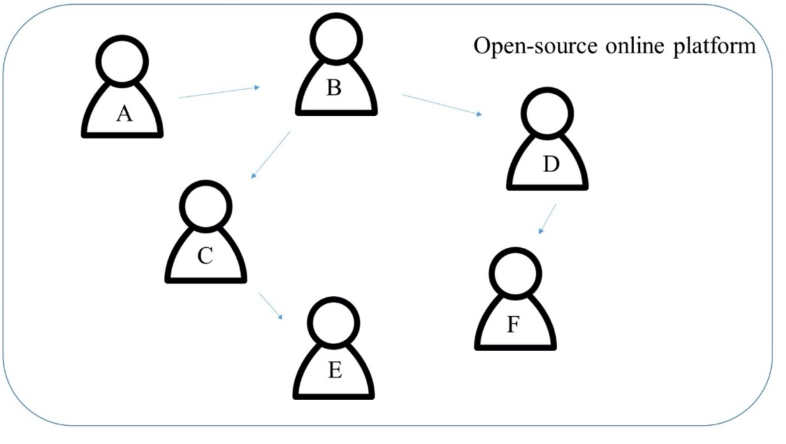
Appendix 1: Model A.1

In the context of 3D printing, production could be organised in a way that digital designing process and physical fabrication process is respectively accomplished by the parties that are strangers with each other. The consumer serves as the coordinator of the whole process. Production in this way is also called the “separation model” in this research.

It is argued that the different way that a consumer combines a source of digital designing with a printing service has a huge impact on product risk. The methods that a consumer can rest on to obtain a CAD file is generalised as “Model A”, while the methods through which the consumer can print out the final product is categorised as “Model B”. Under Model A and Model B, several subcategories can be distinguished.

Model A.1 refers to the case that a consumer can obtain a CAD file from the online open-source community. The CAD file obtained in this way might have been remixed by several parties before it reaches out to the consumer.

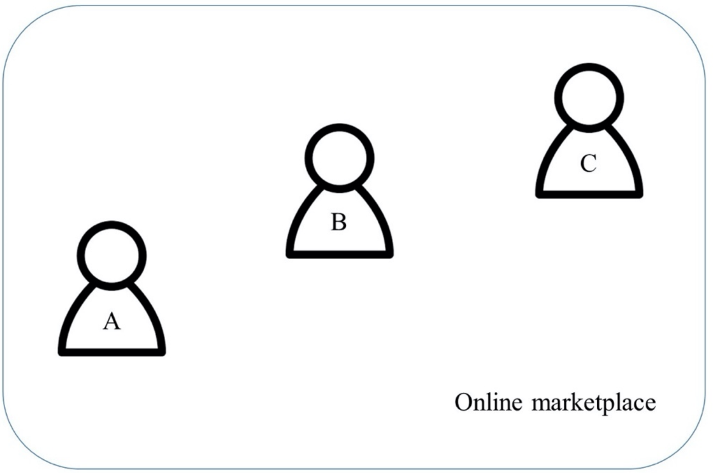
The in-depth introduction of Model A.1 could be seen in Section 3.3.1.



Model A.1: Acquiring a CAD file from an open-source community

Appendix 2: Model A.2

Model A.2 is another way that a consumer can rely on to acquire a CAD file. It specifically refers to the case that a consumer purchases a CAD file from an online marketplace. The in-depth introduction of Model A.2 could be seen in Section 3.3.1.

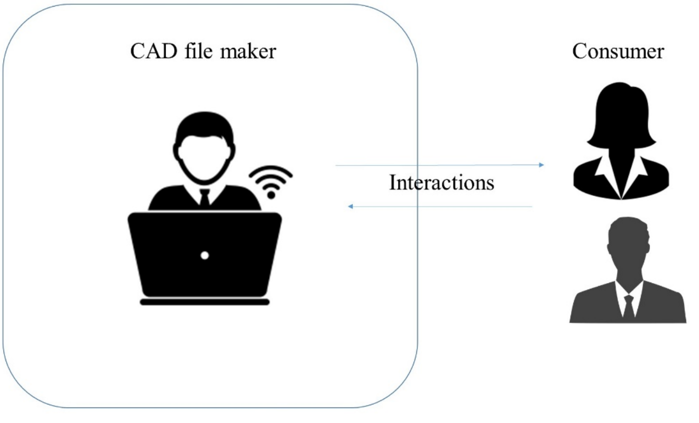


Model A.2: Acquiring a CAD file from an online marketplace

Appendix 3: Model A.3

Model A.3 refers to the case that a consumer aims at customising a CAD file. In Model A.3, the consumer has more chances to talk with the designer about his/her preference. Therefore, the final CAD file reflects the requirement of the consumer to some extent.

The in-depth introduction of Model A.3 could be seen in Section 3.3.1.



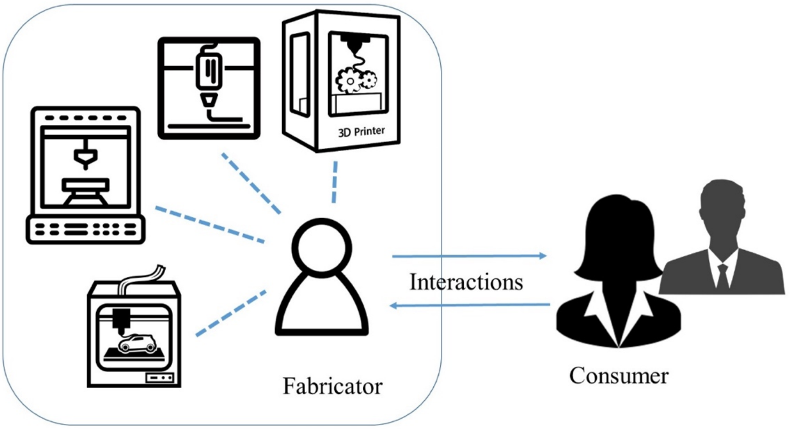
Model A.3: Customising a CAD file with an interactive digital designer

Appendix 4: Model B.1

After a consumer acquires a CAD file from one of the three business models aforementioned, s/he has to take it to a fabricator, who will print out the final product for him. The method used for physical fabrication is generalised as Model B. In general, a CAD file can be transformed into the physical product in one of three methods.

Model B.1 refers to the case that a consumer can contact with a fabricator, who is interactive in the printing process and professional with respect to printing service.

The in-depth introduction of Model B.1 could be seen in Section 3.3.2.

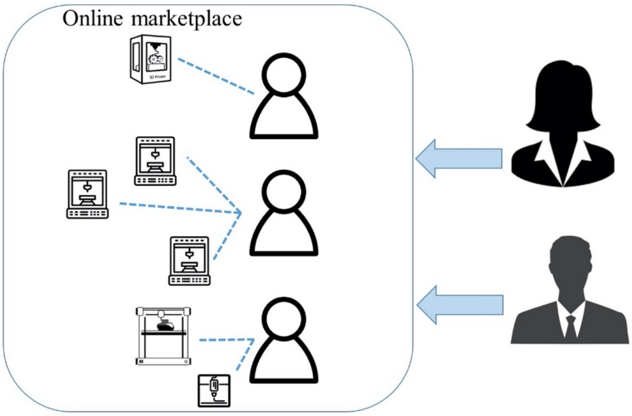


Model B.1: Printing the final product by interacting with a professional fabricator

Appendix 5: Model B.2

Model B.2 refers to the case that the consumer takes the acquired CAD file to a fabricator, who runs a business in an online marketplace.

The in-depth introduction of Model B.2 could be seen in Section 3.3.2.

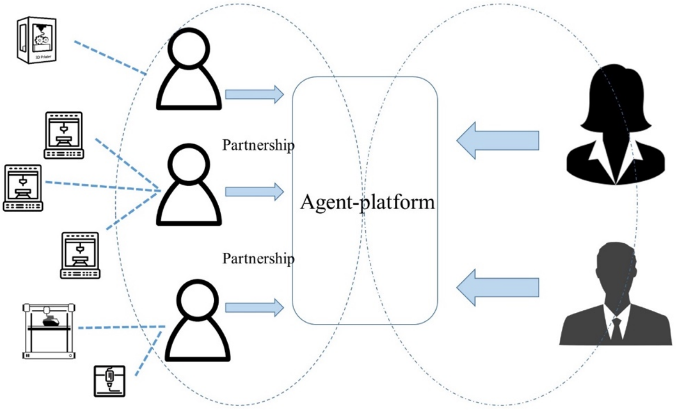


Model B.2: Printing the final product by a fabricator from an online marketplace

Appendix 6: Model B.3

Model B.3 refers to the case that the consumer takes the acquired CAD file to an intermediary platform, and then the platform links this demand to a specific fabricator in cooperation with it. Therefore, the consumer is actually concluding a contract with the intermediary platform and has no chance to contact the fabricator directly.

The in-depth introduction of Model B.3 could be seen in Section 3.3.2.



Model A.3: Printing the final product by contacting an intermediary online platform

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Summary

The trend of digitalisation in recent years has an increasing influence on every aspect of our society. In the domain of production, with the adoption of 3D printing, a product now can be directly fabricated from a CAD file. This transformation not only lowers the threshold of production, thus enabling ordinary people to engage in production activities, but also drives consumers to take a proactive role in directing the process of production by serving as the coordinators between CAD file designers and object fabricators.

The transformation that 3D printing has caused is challenging the incumbent legal regime, which is significantly affected by traditional mass production. This research offers a law and economics explanation for the trade-offs involving the value added and risk generated by 3D printing. It explores the extent to which various legal instruments could be organised to maximise social welfare considering the risk generated by 3D printing. The thesis further provides some implications for the EU legislative framework of the digital single market in the context of 3D printing.

One of the main instruments to deal with product risk is contractual relation. The socially optimal outcome is achieved provided that consumers can communicate smoothly with CAD file designers or fabricators smoothly and that they have a solid understanding of safety information. This thesis explains that under specific business models, contracting over product risk fails to provide contractual parties with optimal incentives. Contracting over product risk is not an efficient instrument in the scenario where consumers obtain a CAD file from an open-source platform and then have a non-professional print the file. In contrast, when production is organised in a way characterised by customisation, contractual parties will be induced to behave more appropriately.

This thesis further shifts to examine the efficiency of tort liability in the context of 3D printing. Tort liability targets producers in the scenario of traditional mass production. Since producers are considered to be the party who can reduce accidents at the lowest cost and who have the capacity to spread the losses, they are required to bear the residual liability and are thus exposed to strict liability. In the context of 3D printing, in a situation where digital designing and physical fabrication are accomplished by a single entity (i.e. under the so-called "one-stop business model"),

applying strict liability might still be desirable. In contrast, for most other business models (i.e. production organised in the so-called "separation models"), because accidents are not unilateral - which means that CAD file designers, fabricators and even consumers may contribute to the damage - it is difficult to define the most suitable party who can efficiently reduce accidents and spread losses. Therefore, the analysis in this thesis indicates that the expansion of strict liability shall not be encouraged.

Other legal instruments assessed in this thesis are regulations and platform governance. Information regulations shall be encouraged in the context of 3D printing, because they could reduce information asymmetry to some extent and thus improve the decision-making of stakeholders. In comparison, due to the prohibitive administrative cost, the use of mandatory standards and prior approval shall be limited to specific areas, such as the medical and mechanical sectors. In addition, platform governance as a new instrument will play an increasingly important role in the digital age with respect to deterrence and risk-shifting. It is noted that, to promote the governance of platforms, legal instruments shall be developed in a way of providing platforms with additional incentives to behave appropriately.

Samenvatting

De trend van digitalisering is de laatste jaren steeds belangrijker geworden, op alle gebieden in onze samenleving. Een van die domeinen is de productie. Zo is het door de introductie van de 3D-printer mogelijk nu direct een product te vervaardigen op basis van een CAD-bestand. Deze transformatie verlaagt niet alleen de drempel tot productie, waardoor ook gewone mensen nu voorwerpen kunnen produceren; het stimuleert consumenten ook om proactief aan het productieproces deel te nemen door als coördinator op te treden tussen CAD-ontwerpers en makers van objecten.

De transformatie die 3D-printen heeft veroorzaakt vormt een uitdaging voor het huidige wettelijke kader, dat in verregaande mate door de traditionele massaproductie beïnvloed is. In dit onderzoek wordt een juridische en economische verklaring gegeven van de afwegingen tussen de toegevoegde waarde en het risico van 3D-printen. Onderzocht wordt in welke mate verschillende juridische instrumenten zouden kunnen worden ingezet om het maatschappelijk welzijn te maximaliseren, gezien het risico van 3D-printen. Dit proefschrift biedt verder enkele implicaties voor het wetgevingskader van de EU voor de digitale gemeenschappelijke markt als het gaat om 3D-printen.

Een van de belangrijkste instrumenten voor het omgaan met productrisico is het contract. Een maatschappelijk optimale uitkomst wordt bereikt mits de consument soepel met de CAD-ontwerper en fabrikant kan communiceren en de veiligheidsinformatie goed begrijpt. In dit proefschrift wordt uitgelegd dat bij bepaalde bedrijfsmodellen het contractueel vastleggen van productrisico niet zorgt voor optimale prikkels voor de contractpartijen. Het contractueel vastleggen van het productrisico is geen efficiënt instrument voor een scenario waarin consumenten een CAD-bestand van een open source platform halen en het product vervolgens door een niet-deskundige laten printen. Als er daarentegen productie op maat plaatsvindt, dan worden de contractpartijen gestimuleerd zich correcter te gedragen.

Vervolgens wordt in dit proefschrift de effectiviteit van aansprakelijkheid voor een onrechtmatige daad in het kader van 3D-printen onderzocht. Aansprakelijkheid op basis van een onrechtmatige daad is gericht op fabrikanten die traditionele massaproductie leveren. Aangezien de fabrikant als de partij wordt beschouwd die het ongevalsrisico tegen de laagste kosten kan reduceren en het verlies kan spreiden, wordt deze verplicht de subsidiaire aansprakelijkheid op zich te nemen en wordt dus aan risicoaansprakelijkheid blootgesteld. Bij 3D-printen, in de situatie waarin het digitale ontwerp en de fabricage van het fysieke object door dezelfde entiteit worden uitgevoerd (het zogenaamde alles-in-één-bedrijfsmodel), kan het toepassen van risicoaansprakelijkheid nog steeds wenselijk zijn. Bij andere bedrijfsmodellen daarentegen (d.w.z. fabricage volgens een zogenaamd gescheiden model) is het moeilijk te bepalen welke partij het ongevalsrisico kan reduceren en het verlies kan spreiden, omdat ongevallen niet unilateraal zijn; de CAD-ontwerper, de producent en zelfs de consument kunnen aan de schade bijdragen. De analyse in dit proefschrift geeft daarom aan dat het uitbreiden van risicoaansprakelijkheid niet moet wordt aangemoedigd.

Andere juridische instrumenten die in dit proefschrift worden beoordeeld zijn regulering en platformbeheer. Informatievoorschriften voor 3D-printen moeten worden aangemoedigd, omdat die de informatie-asymmetrie enigszins kunnen verkleinen en op die manier voor betere besluitvorming bij de betrokken partijen kunnen zorgen. Gezien de onbetaalbaar hoge administratieve kosten zal het gebruik van verplichte standaarden en goedkeuring vooraf tot specifieke gebieden worden beperkt, zoals de medische sector en de machinebouw. Daarnaast zal platformbeheer als nieuw instrument een steeds grotere rol gaan spelen in het digitale tijdperk wat betreft afschrikking en risicoverschuiving. We merken op dat om platformbeheer te stimuleren er juridische instrumenten moeten worden ontwikkeld, zodat platformen extra prikkels krijgen om zich correct te gedragen.

Curriculum vitae

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Short bio	
Shu Li (Changshu, 1989), is a PhD candidate in law & Economics at Erasmus University Rotterdam. Before joining Erasmus University, Shu gained a law degree at China University of Political Science and Law (CUPL) and a master of intellectual property law at the same university. Shu's research focus on the law and economics analysis of tort law and risk regulation, especially in the context of emerging disruptive technologies such 3D printing, artificial intelligence and robotics. During his PhD trajectory, Shu published articles in leading international and Dutch journals. He was also invited to present his research in top universities, institutions and international conferences.	
Education	
European Doctorate in Law and Economics. Joint Degree at Erasmus University Rotterdam; University of Hamburg and University of Bologna	2015-2020
Master of Intellectual Property Law, China University of Political Science and Law	2012-2015
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Work experience	
Trainee at Greenberg Traurig, LLP (Amsterdam Office)	2020
Teaching Assistant at China University of Political Science and Law	2014-2015
Intern at the Supreme Court of China	2011
Prizes and awards	
China Scholarship Council (CSC) Scholarship	2015-2019
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Publications	
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Risk-shifting in the context of 3D Printing: An Insurability Perspective (with Michael Faure), in *Geneva Papers on Risk and Insurance*. 45, 482–507.	2020

What Shall we do with the Drunken Sailor? Product Safety in the Aftermath of 3D Printing (with Klaus Heine), in *European Journal of Risk Regulation*, 10 (1), 23-40.	2019

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PhD training

Bologna courses	*year*
Experimental Law and Economics (Prof. Marco Casari)	2016
Introduction to Statistics (Prof. Alessandra Giovagnoli)	2016
Modelling European Private Law (Prof. Francesco Parisi)	2016
European Competition Law and Intellectual Property Rights (Prof. Alberto de Pra)	2016
Game Theory and Law (Prof. Emanuela Carbonara)	2017
Behavioural Law & Economics and Enforcement (Prof. Paolo Vanin)	2017
Specific courses	***year***
Seminar ‘How to write a PhD’ (Rotterdam)	2016
Academic Writing Skills for PhD students (Rotterdam)	2016
Tort Law and Economics (Prof. Luigi Franzoni, University of Bologna)	2016
Workshop on Applied Maths and Matrix (University of St. Gallen)	2017
Workshop on Statistics with R (University of St. Gallen)	2017
Regression Analysis I & II (University of St. Gallen)	2017
Seminar Series ‘Empirical Legal Studies’ (Prof. Jonathan Klick and Dr. Jaroslaw Kantorowicz)	2018
Economic Analysis of Public Law (Dr. Elena Kantorowicz-Reznichenko)	2018
Property Law and Economics (Prof. Boudewijn Bouckaert, Rotterdam)	2019
Seminars and workshops	***year***
Bologna November seminar (attendance)	2016
BACT seminar series (attendance)	2016-2020
EGSL lunch seminars (attendance)	2016-2020
Joint Seminar ‘The Future of Law and Economics’ (attendance)	2017-2018
Rotterdam Fall seminar series (peer feedback)	2017
Rotterdam Winter seminar series (peer feedback)	2018
Presentations	***year***
Bologna March seminar	2017
Hamburg June seminar	2017
Rotterdam Fall seminar series	2017

Rotterdam Winter seminar series	2018
Bologna November seminar	2018
EGSL Lunch Lecture Series	2017-2018
EDLE Openning Seminar	2018
Presentations in international conferences	***year***
When the Innovation-Related Regime Meets the Age of 3D Printing: An Analysis of Law and Economics, 11th Annual Conference of European Policy for Intellectual Property, Pembroke College, Oxford University, UK	2016
3D Printing Damages and Compensatory Instruments, in The Future of Law and Economics Conference, Erasmus University Rotterdam, Rotterdam, the Netherlands.	2018
Risk-shifting in the Context of 3D Printing, in 18th Joint Seminar of the European Association of Law and Economics and the International Association for the Study of Insurance Economics (The Geneva Association), Catholic University of the Sacred Heart, Milan, Italy	2019
Will a Digital Designer be Strictly Liable in the Context of 3D Printing?, in 24th Ius Commune Annual Conference, KU Leuven, Leuven, Belgium	2019