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DEVELOPMENT AND APPLICATION OF A COMPUTER-BASED METHODOLOGY FOR DESIGN FOR ADDITIVE MANUFACTURING OF AUTOMOTIVE COMPONENTS

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Abstract

The research project is focused on the development and application of a computer-based methodology to support the Design for Additive Manufacturing of metal components for the automotive sector. Firstly, the scenario of Additive Manufacturing is depicted, describing its role in the current era of Industry 4.0 and in particular focusing on Metal Additive Manufacturing technologies and the Automotive sector applications. Secondly, the state of the art in Design for Additive Manufacturing is described, contextualizing the methodologies, and classifying guidelines, rules, and approaches. The key phases of product design and process design to achieve lightweight functional designs and reliable processes are deepened and the Computer-Aided Technologies to support the approaches implementation are presented. Therefore, a general Design for Additive Manufacturing workflow based on product optimization and process optimization has been systematically defined. From the analysis of the state of the art, the use of a holistic approach has been considered fundamental and thus the use of integrated product-process design platforms has been evaluated as a key element for its development. Indeed, a computer-based methodology exploiting integrated tools and numerical simulations to drive the product and process optimization has been proposed. A validation of CAD platform-based approaches at different levels has been performed, as well as potentials offered by the integrated tool have been evaluated. Concerning product optimization, systematic approaches to integrate topology optimization integration in Design for Additive Manufacturing have been proposed and validated through product optimization of an automotive case study to be produced by laser Powder Bed Fusion. Concerning process optimization, the use of process simulation techniques to prevent manufacturing flaws related to the high thermal gradients of metal processes is developed, providing case studies to validate results compared to experimental data. The method is applied to perform the process optimization of an automotive case study to be produced by laser Powder Bed Fusion. Finally, an example of product and process design performed through the proposed simulation-driven integrated approach is provided to prove the method's suitability for effective redesigns of Additive Manufacturing based high-performance metal products. The results are then outlined, and further developments are discussed.

1 Scenario: Metal Additive Manufacturing

1.1.1 Additive Manufacturing

Additive Manufacturing (AM), as opposed to subtractive manufacturing, is a set of technologies to produce parts adding material layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies [ISO 52900] It has been called also Freeform Fabrication or Additive Layer Manufacturing, and most people know it as 3D Printing. Actually, the last name is improper, because 3D Printing (Three-Dimensional-Printing) is the registered name of Binder Jetting (BJ), a process developed by the Massachusetts Institute of Technology and patented in 1993. In fact, AM technologies are not so innovative, since the first processes were developed back in the 80s and in 1984 parallel patents concerning layer by layer fabrication were filed in Japan, France, and USA. In 1987, the American company 3D Systems commercialized the “Stereolithography”, which is universally recognized as the first AM process. From the late 80s, AM technologies started to spread, giving rise to applications that are known as Rapid Prototyping (first 90s), Rapid Tooling (late 90s), and Rapid Manufacturing (early ’00). The roadmap from Rapid Prototyping to the current Digital Manufacturing goes hand in hand with technological improvements. Firstly, AM was been massively used for visualizing product concepts or building aesthetic prototypes in the last decades. Subsequently, the evolution of machines and materials enabled the construction of parts that can both fit in assemblies, due to the improvements in accuracy, and perform functionality, due to the better mechanical properties. This process is the achievement of the so-called “3 Fs” rule: form, fit, and function [Gibson 2010]. In 2009 the American Society for Testing Materials (ASTM) committee F42 published a document containing the standard terminology on Additive Manufacturing establishing it as an industrial manufacturing technology. Currently, AM technologies can be used to transform almost every material, such as polymers, metals, or composites. They can be either additively manufactured final components or tools to support most common manufacturing technologies (e.g. models, inserts, cores, and molds respectively for injection molding, casting, composites lamination). Since the last decade, the technology evolution has ramped up and nowadays the innovation is their extension to a real manufacturing system for final products.

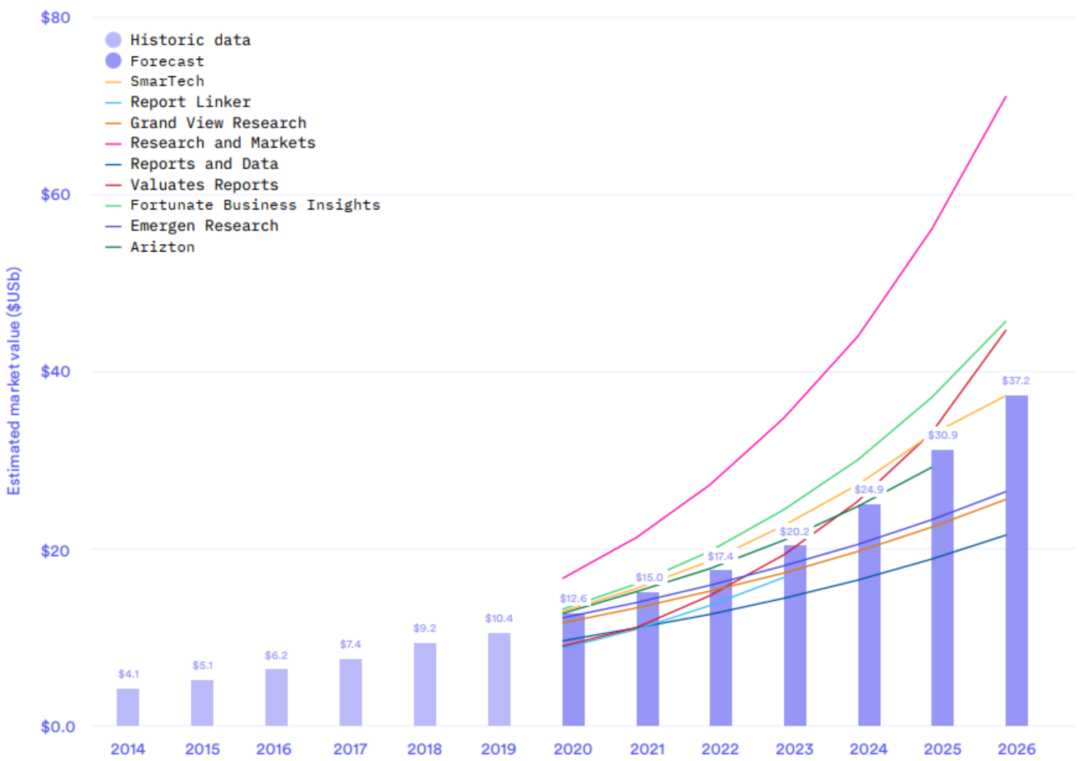
1.1.2 3rd industrial revolution & Industry 4.0

The direct connection between a CAD model and a functional physical part provides a reduction of investment costs, development time, and modification time and costs. This leads to re-think product business models, due to the great potentials of high differentiation, high flexibility, high specificity, and high customization. The whole thing is based on the idea that a bi-dimensional shape is easy to build, no matter the tri-dimensional geometric complexity. In literature, we speak about “complexity for free” due to this enhanced design freedom, and thus, it is possible to imagine every type of object and build it directly. The benefits concern not only the product but also production and logistics. Firstly, complex and performant products, small batches production, and customized production become feasible by removing manufacturing traditional process constraints. Moreover, production can occur in less quantity, in many places, more late (Just-In-Time), potentially with fewer waste materials, less energy, and fewer goods transport and storage. In 2012 The Economist wrote that, as manufacturing goes digital, a third great change is gathering space and we can speak about the “third industrial revolution”. The industrial scenario is therefore moving from “mass production” to “mass customization” [Milewski 2017]. To sum up, Rapid Prototyping is based on design communication, fast design iterations, and low-cost prototypes construction. Whereas Additive Manufacturing must exploit few design restrictions, parts customization, on-demand production, or even distributed manufacturing. Indeed, we are currently inside the “Industry 4.0” era, where Additive Manufacturing plays a prominent role among the key driving technologies.

The Industry 4.0 enabling technologies constitute the so-called “nine pillars” [Rüßmann 2015], and it is tied to all the other pillars whether they can be used directly (for AM applications) or indirectly (with AM processes) [Butt 2020]:

- Additive Manufacturing;
- Augmented Reality;
- Autonomous Robots;
- Big Data and Analytics;
- Cybersecurity;

- Horizontal and Vertical System Integration;
- Industrial Internet of Things;
- Simulation;
- The Cloud.



Footnote:
* The historic market size was calculated by averaging the market size reported by Wohler's Associates[01] and SmarTech[04].
** The forecasted market size in the median market size reported by all market analysts.
*** Links to all sources can be found under the References section of this report.

Figure 1: the Additive Manufacturing market forecast [3D hubs 2020]

A report of 2020 trends provides an impressive 24% forecasted average annual growth of Additive Manufacturing for the next five years, calculated by notable rating agencies such as Wohler's, Ernst & Young, and SmarTech [3D hubs 2020]. From 2012 to 2018 [Ceulemans 2020], we moved from 1413 AM-related related research publications to 9228. In the same period, the AM-related patents applications moved from 818 to 4072 [Schmitt 2021]. Moreover, Wohler's report 2021 shows exponential growth in the production of AM parts in the last decade, from 500 to more than 5000 million dollars [Wohlers 2021]. Those data confirm the topic's centrality in both academy and industry.

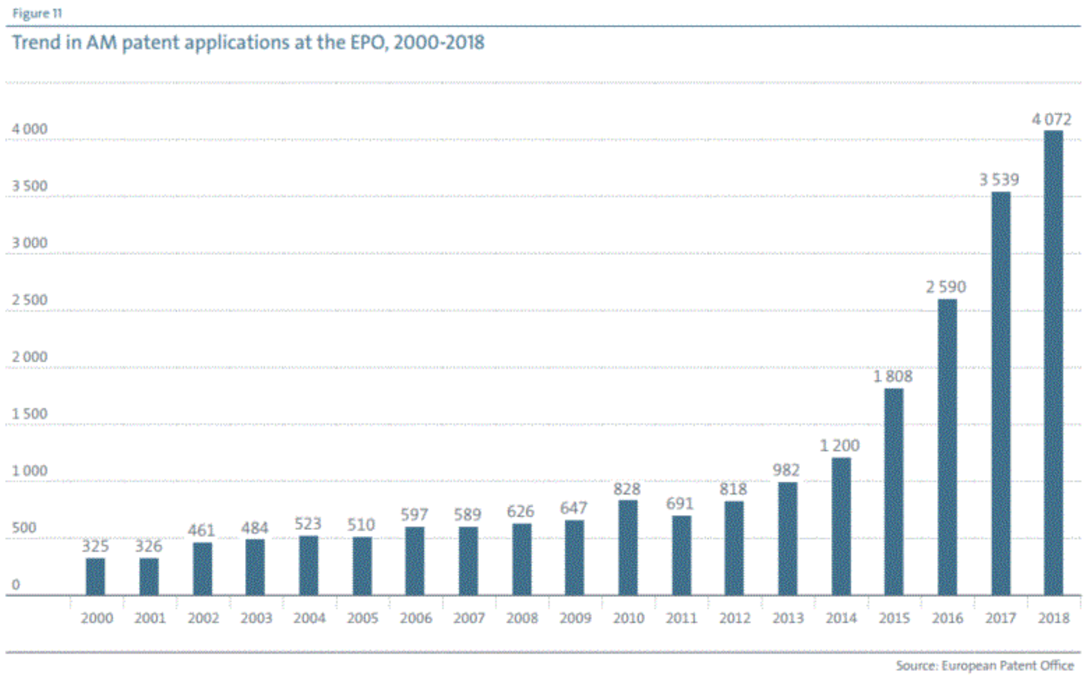


Figure 2: The trend in AM patent application [Ceulemans 2020]

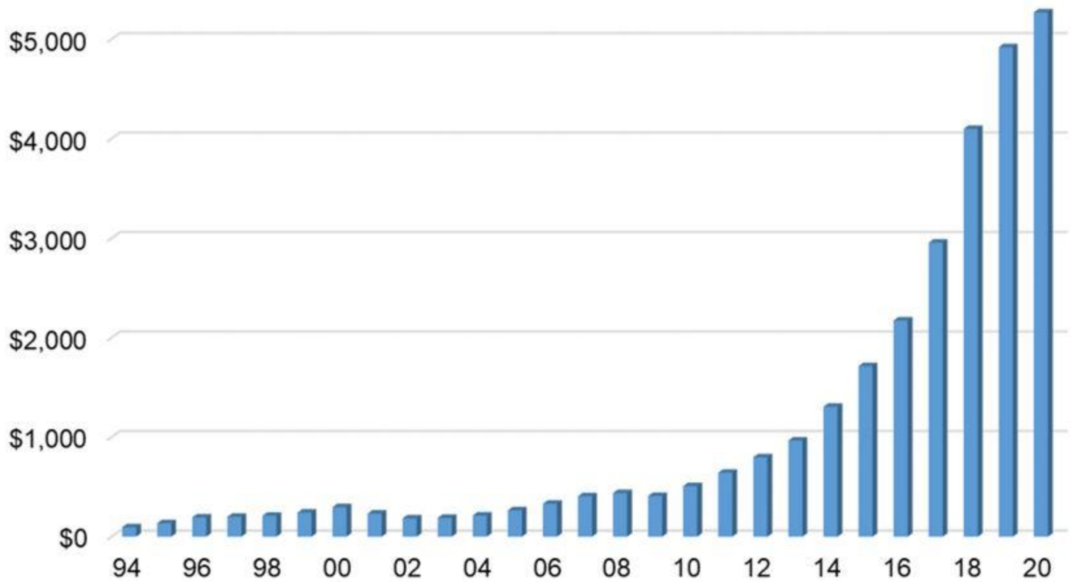


Figure 3: The production of Additive Manufacturing parts [Wohlers 2021]

1.2 Metal AM

Metalworking was born in the stone age and consolidated through the Neolithic, the bronze age, and the iron age. In this period, it has always been based on casting and forging, without disruptive innovations. In the 1700s, there were important evolutions in the alloys, whereas from the late 1800s processes have seen improvements, but keeping the forming or subtracting approaches. Just from the 90s of the XX century, the first metal additive manufacturing process could revolutionize the design and production of objects. The first metal part was built by Bourell and Frayre at the University of Texas, by exploiting the knowledge of the Laminated Object Manufacturing (LOM) process, which has been commercialized by Helisys since 1991. Today, Metal Additive Manufacturing can be used to create complex parts providing functional and optimized structures [Gao 2015, Ngo 2018]. Design for Additive Manufacturing approaches should be involved for this purpose, to exploit the design freedom induced by the technologies. The most prominent sectors that benefit from such high-performance parts are the aerospace, the medical field, and the automotive. Aerospace benefits from complex geometries, lightweight designs, and advanced materials. Whereas medicine takes advantage of the high customization and specific designs due to patients' different morphological characteristics. Moreover, new industrial applications are continuously arising in sundry sectors, such as energy, oil & gas, production, remanufacturing and repairing, tools and molds, and structures. Or even industrial design, architecture, artistic design, or customized design.

The rest of the chapter is structured as follows. Additive Manufacturing based processes to produce metal parts, which are at the heart of this thesis, are summarized. The most prominent ones, which will be treated within the work, are described, along with their advantages and disadvantages. Finally, the use of Metal Additive Manufacturing in the Automotive setting, as well as current and forthcoming applications and challenges, are discussed.

1.2.1 Metal AM Processes

In order to report the processes to use AM technologies to produce metal parts, hereinafter we consider the classification proposed by the ASTM F2792 standard [ASTM F2792]. The standard developed by the ASTM F42 committee classified all the AM technologies into seven categories: Material Extrusion, Vat Photopolymerization, Material Jetting, Binder Jetting, Powder Bed Fusion, Directed Energy Deposition, Sheet Lamination.

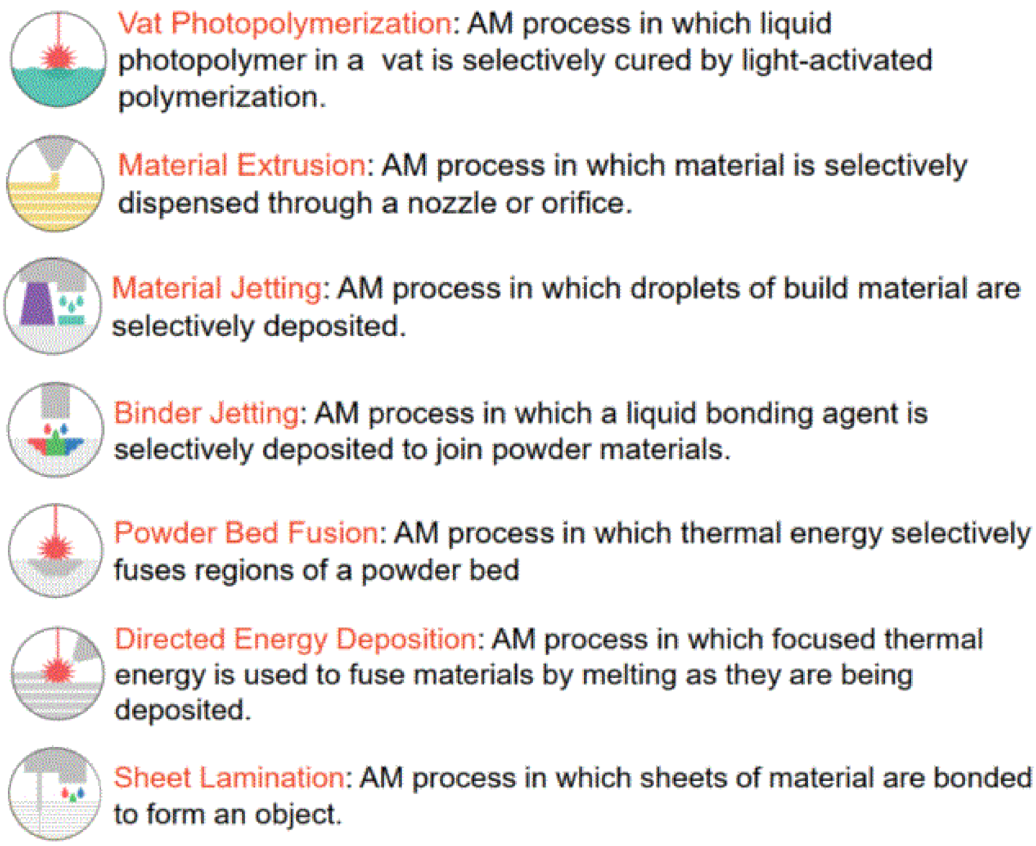


Figure 4: The Additive Manufacturing categories according to the ASTM F2792 [3DHubs 2017]

Table 1 provides information for each of the seven categories, such as the basic working principle, the processed materials, and the main technology examples.

Table 1: Working principle, processed materials, and the main technology examples.

ASTM Category	Basic principle	Materials	Technology examples
BJ	*process in which a liquid bonding agent is selectively deposited to join powder materials*	• polymers • ceramics • composites • metals	3DPrinting, S-Print, M-Print,
DED	*process in which focused thermal energy is used to fuse materials by melting as they are being deposited*	• metals	Laser Deposition / Laser Metal Deposition / Direct Metal Deposition, Laser Engineered Net Shaping.
ME	*process in which material is selectively dispensed through a nozzle or orifice*	• polymers • composites • metals	Fused Filament Fabrication / Fused Deposition Modeling
MJ	*process in which droplets of build material are selectively deposited*	• polymers • metals • wax	Polyjet, NanoParticle Jetting, Drop On Demand
PBF	*Process in which focused thermal energy selectively fuses regions of a powder bed*	• metals • polymers • ceramics	Selective Laser Melting / Direct Metal Laser Sintering, Selective Laser Sintering, MultiJet Fusion
SL	*process in which sheets of material are bonded to form an object*	• paper • polymers • metals	Laminated Object Manufacturing Ultrasonic Additive Manufacturing
VP	*process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization*	• polymers	StereoLithography, Digital Light Processing, Continuous Liquid Interface Production

Most of the technologies can be used to produce metal parts, by following two approaches:

- direct processes;
- indirect processes.

The formers are used to directly create metal end-use parts, while the latters involve AM technologies in processes composed of sequential steps to obtain the final components. The most widespread direct processes are Powder Bed Fusion and Directed Energy Deposition, but they present different potentials and thus they are suitable for different applications. Moreover, we can find Sheet Lamination, to which the first metal process belongs, but also Material Extrusion, Material Jetting, and Binder Jetting can be combined with specific post-processing to obtain final parts. Finally, Material Extrusion and Material Jetting can be used also for indirect processes, as well as the least, or rather Vat Photopolymerization.

1.2.1 Direct processes

1.2.1.1 Powder Bed Fusion

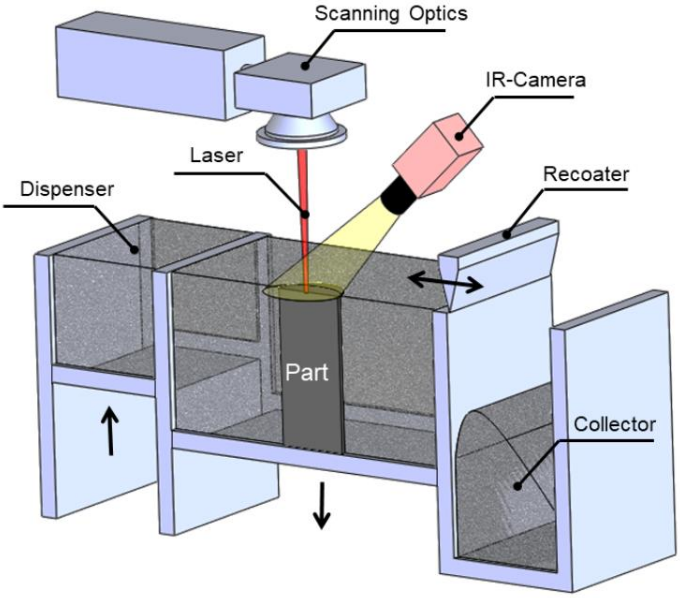


Figure 5: A PBF process [Razavykia 2020]

Powder Bed Fusion (PBF) is an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed [ASTM 2792]. The development of the process started in 1995 at the Fraunhofer Institute ILT in Germany. The energy source can be either a laser or an electron beam, thus, we can generally speak about laser-based PBF (L-PBF or PBF-L) or electron beam-based PBF (EB-PBF or PBF-EB). The most common laser-based process is the Selective Laser Melting (SLM [SLM]), also known as Direct Metal Laser Sintering (DMLS [EOS]), Lasercusing [Concept Laser], or Direct Metal Printing (DMP [3D Systems]. While for the electron beam based, the Electron Beam Melting (EBM [Arcam]) is the most used. Actually, Powder Bed Fusion is the most used technology to produce metal components. Among the advantages of PBF, firstly we must consider the feasibility to build complex shapes and structures, that make it suitable to produce high-performance components integrating functional design. Moreover, the process entails quite high parts accuracy and high materials mechanical properties. Finally, the build preparation is quite simple and multiple instances or different components can be introduced in one build job. Thus, it provides high flexibility, and it can be used to rapidly create functional metal prototypes. The disadvantages are related to parts size limits, and slow deposition rates that, joined with the cost of powder material, make the technologies very expensive. Currently, machines and material costs are reducing, shifting the breakeven point of economic advantage towards larger and larger batches. Furthermore, it is important to mention the non-optimal reliability of the processes, related to material defects formation and parts distortion, and residual stress, that can compromise functionality. Details about the PBF process can be found in [Sun 2017]

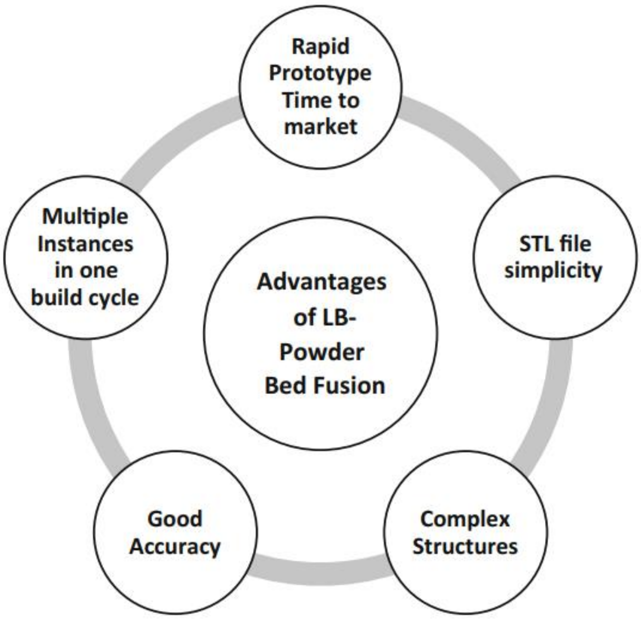


Figure 6: Advantages of a PBF process [Milewski 2017]

1.2.1.2 Directed Energy Deposition

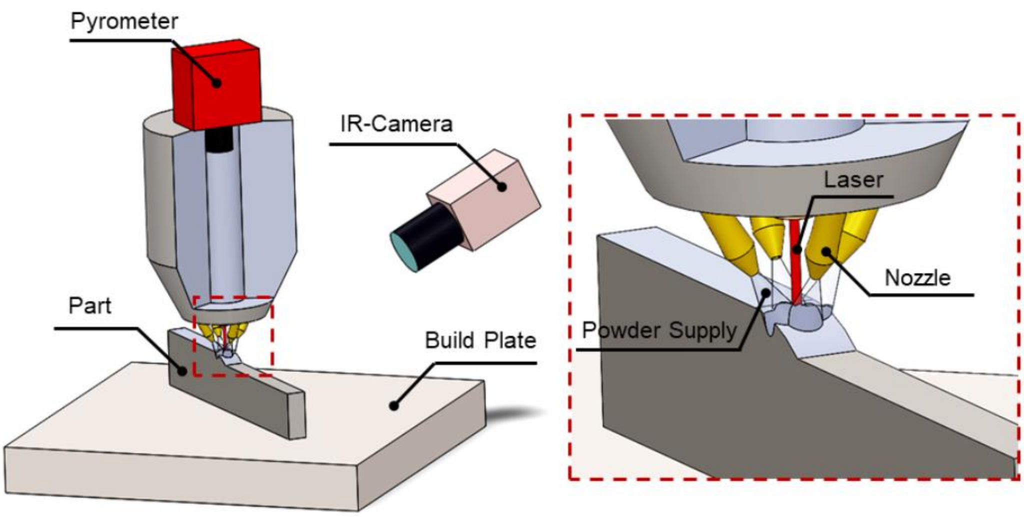


Figure 7: A DED process [Razavykia 2020]

Directed energy deposition (DED) is an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited [ASTM F2792]. The process is set up to produce components in an analog manner to welding or cladding technologies such as plasma welding or laser cladding. Directed Energy Deposition processes are classified considering the type of feedstock and the type of energy source. The feed material can be either powder or wire, whereas the melting process can be fulfilled by a laser beam, an electron beam, or even a plasma or electric arc. The most common processes are powder and laser-based DED (L-DED or DED-L), among which we can find the Direct Metal Deposition (DMD [DM3D Technology], the Laser Engineered Net Shape (LENS [Optomec]), the Laser Metal Deposition (LMD). The most used wire-based process is the Wire Arc Additive Manufacturing (WAAM [Waammat]), whereas the most important electron beam–based (EB-DED or DED-EB) one is the Electron Beam Additive Manufacturing (EBAM [Sciaky]). Directed Energy Deposition processes are often used to create large parts and constructions. In particular, deposition heads can be integrated into robotized cells to create the largest additively manufactured metal structures. Moreover, they can be used for the reparation of damaged components [Saboori 2019] or even for the remanufacturing of existing components to produce high-performance design variants [Polenz 2019]. Finally, they can be integrated with CNC milling equipment to create hybrid Additive-Subtracting technologies. Among the advantages of DED, we must therefore mention the high deposition rates, but also the possibility to process a wide range of powders and combine them to create multi-materials and graded materials. For example, Functionally Graded Materials (FGM) can improve wear and corrosion resistance, hardness, or thermal properties [Piscopo 2022]. On the side disadvantages, we have fewer complex shapes and fewer parts accuracy, as well as limitations regarding the CNC programming. Also, we should mention the presence of material defects and residual stress and distortions, particularly significant for large structures. Details about the DED process can be found in [Dass 2019, Jafari 2021, Piscopo 2022]

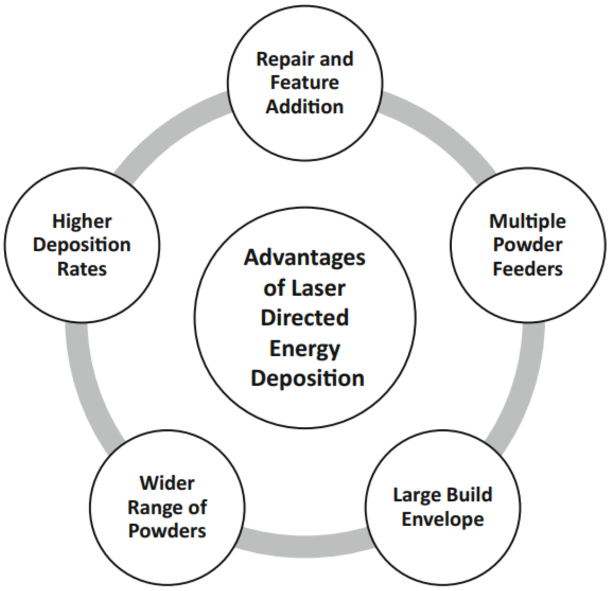


Figure 8: Advantages of a DED process [Milewski 2017]

1.2.1.3 Other

Other processes used to a less extent to produce metal parts are going to be introduced. Material Extrusion (ME) is an additive manufacturing process in which material is selectively dispensed through an orifice [ASTM F2792]. A process that belongs to this category is the Metal Fused Filament Fabrication (M-FFF). A metal powder and polymer mixture wire is fused, extruded through a nozzle, and deposited onto a build plate. It is used to produce green parts, that are subsequently sintered through specific machines. Material Jetting (MJ) is an additive manufacturing process in which droplets of build material are selectively deposited [ASTM F2792]. The Nanoparticle Jetting (NJ [Xjet]) process belongs to this category. A liquid containing nanoparticles of metal is dispensed to build green parts, the high temperature makes the liquid evaporate, and finally, the parts are sintered in the oven. Binder Jetting is an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials [ASTM F2792]. In Metal Binder Jetting (M-BJ) a green part is created starting from metal powder, afterwards, specific post-processing is required. Firstly, a curing or sintering phase to make the parts stronger, and finally an infiltration phase, generally by metal bronze, to achieve the final density. As mentioned before, the term “3D Printing” was originally coined by MIT about Metal Binder Jetting technology. In general, these processes produce parts with lower mechanical properties and variable dimensional and geometrical accuracy, depending on shrinkage management. Nevertheless, they can be significantly cheaper since they do not use costly lasers, electron beams, gas, or vacuum. Also, they are less prone to residual stress issues, and they can be reliable for proper flexible and production-capable applications. Finally, we must cite the category to which LOM process belongs, or rather Sheet Lamination, an additive manufacturing process in which sheets of material are bonded to form an object [ASTM F2792].**1.2.1.4 Indirect**

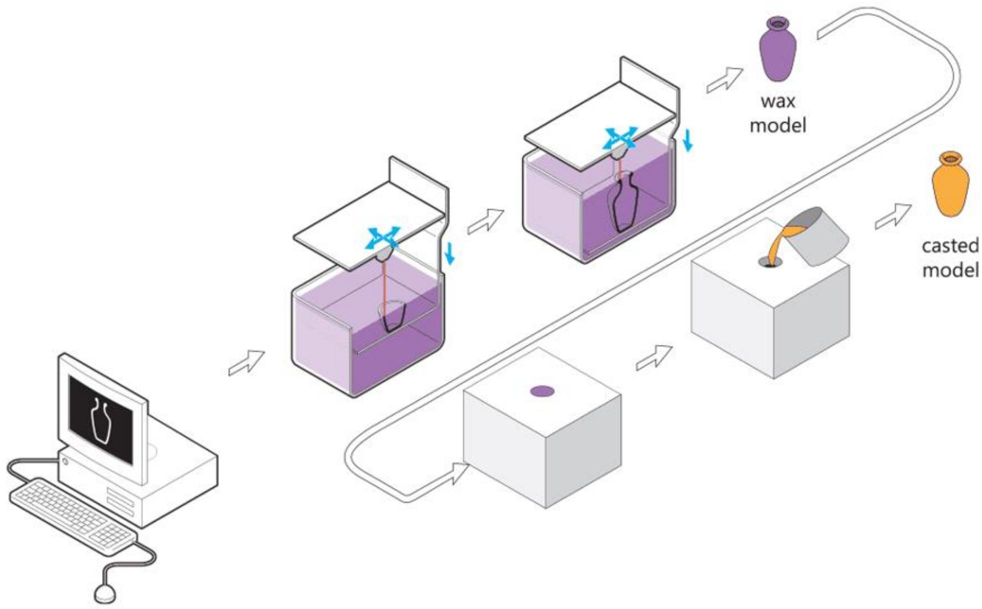


Figure 9: A lost-wax cast process

Indirect processes exploiting AM technology are mostly those known as rapid casting [Gao 2021]. AM is used to support traditional technologies such as metal foundry, by producing proper tools [Chhabra 2011]. In Quick-Cast, lost-wax models or mold patterns for investment casting processes can be produced through Material Jetting or Photopolymerization processes. Concerning the first, Drop On Demand (DOD) processes provide the deposition of layers of wax on a build plate and subsequent milling or leveling to achieve very precise shapes. Regarding the second, Photopolymerization is an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization [ASTM F2792]. Stereolithography (SLA, or SL), Direct Light Processing (DLP), or Continuous Liquid Interface Production (CLIP) belong to this category and can be used for this purpose. Even lost-PLA models can be produced for this purpose, with the advantage of the use of very accessible, cheap, and reliable technologies (i.e. Fused Filament Fabrication (FFF) / Fused Deposition Modeling (FDM)) and materials (Polylactic Acid). In Rapid Sand Casting, parts models, cores, and molds for sand casting can be produced by polymer AM. Parts models to perform the sand molds forming can be produced quickly and cheaply. Molds to produce sand cores can be easily built, or even direct construction of the cores can be performed, for example by BJ processes. In Direct Metal Casting, the complete molds and cores assembly can be directly produced by a specific AM technology [ZCast] and, afterward, the molten metal pouring can occur.

Figure 10: A Direct Metal Casting Process [ZCast]

1.3 The Automotive sector

The Automotive sector is highly technology-intensive, competitive, and involves a large supply chain, thus, despite the complexity, it has a huge impact on AM business models evolution. Back in 2014, Deloitte provided a perspective of current and future trends for AM in the sector, considering the vehicle system [Giffi 2014]. Starting from back applications, they already identified categories such as exteriors (bumpers, windbreakers, etc.), fluid handling (pumps, valves, etc.), manufacturing process (prototyping, customized tooling, investment casting, etc.), exhaust (cooling vents, etc.). Then they have foreseen further categories for future applications. Interior and seating, including dashboards and seat frames. Wheels, tyres, and suspension, from hubcaps to tires to suspension springs. Electronics, considering embedded sensors or control systems. OEM components, considering the production of spare parts from the entire Body-In-White, or frame, body, and doors applications. Finally, they expected the development of drivetrain and powertrain components, from transmission to engine components. Moreover, an automotive AM application that has not been mentioned, but is interestingly growing is about replication of components for classic car restoration.

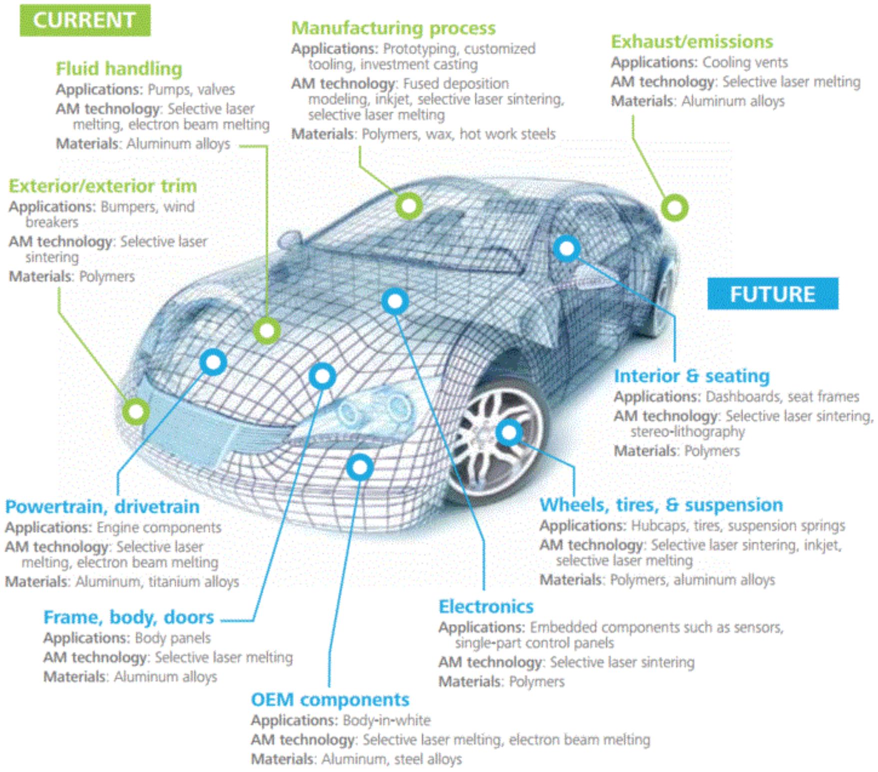


Figure 11: The Deloitte analysis [Giffi 2014]

Nowadays, many of the listed categories have been developed and most of them provide not only research case studies and prototypes. Most cases concern small batches of high-performance components or highly customized parts, but there is no shortage of applications in normal production lines. In fact, just five years later, Wohlers reported that in 2019 28.4% of Additive Manufacturing output achieves functional end-use components [Wohlers 2019]. For example, in 2018 BMW reported on its one millionth additively manufactured component in series production. AM automotive applications can be also analyzed considering the product lifecycle, from design concept to design generation, manufacturing support, manufacturing processes, and maintenance. In fact, in 2020 Delic et al. stated that product visualization was already consolidated, but applications in prototyping, tooling, direct part manufacturing, and maintenance and repair are going to spread within the next 10 years [Delic 2020].

1.3.1 Current Automotive Applications

We can trace the achievement of milestones concerning the challenging categories above mentioned through different examples of real applications. Application of AM technologies for exterior and interior specific components and prototypes is consolidated and we can find also a widespread of specific tooling for production lines. Very specific production is the case of reproduction of rare or unique components for classic cars restoration made possible by combining AM, 3D capturing, and Reverse Engineering techniques.

Figure 12: Components reproduction for Mercedes classic cars restoration

Figure 13: Components reproduction for Porsche classic cars restoration

Porsche classic and Mercedes-Benz provide sundry examples. The motorsport renowned company Sauber currently stakes on the historic vehicle sector reproducing classic cars components. A case from a powertrain is the gearbox housing of a 1950s Ferrari 350 America Barchetta. They performed the Reverse Engineering of the housing by 3D scanning, and they built the component in aluminum alloy by the laser-based PBF process of Additive Industries. The process flow of components reconstruction is depicted in Figure 14.

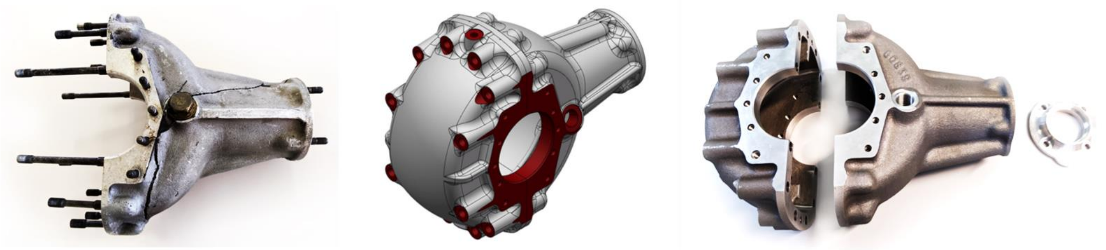


Figure 14: Gearbox reconstruction based on
Reverse Engineering and Additive Manufacturing

Volkswagen, Audi or Ford introduced customized fixtures and jigs to improve assembly operations efficiency and ergonomics. As regarding customization, interesting examples are the Volkswagen wheels for the Microbus, or even the Mini sidebands and inserts currently available for the customers' personalization.

Figure 15: The Volkswagen wheel and the Mini sideband

Figure 16: Porsche’s seats with customized compounds

Porsche is the first company to offer seats with customized compounds in 2021. Speaking about wheels and suspensions, we can find Michelin’s Uptis wheel prototype to eliminate the risk of puncture or the integrated wheel carrier and brake caliper design concept from FCA, that implements consolidation of 12 components non-suspended mass saving.

Figure 17: The Michelin’s Uptis and the integrated wheel carrier from FCA

Moving to frame, body, and structures, we can find several examples of lightweight design. From niche series production of the custom BMW s1000rr frameset or the

APworks's light rider, an electric motorbike presenting an impressive weight of 60 kilos, to actual production parts.

Figure 18: The APWorks "Light riger" and the BMW s1000rr

The roof bracket of the BMW i8 Roadster electric supercar is an example of an additively manufactured end-use component, combining a high stiffness to weight ratio and futuristic design, currently in normal production.

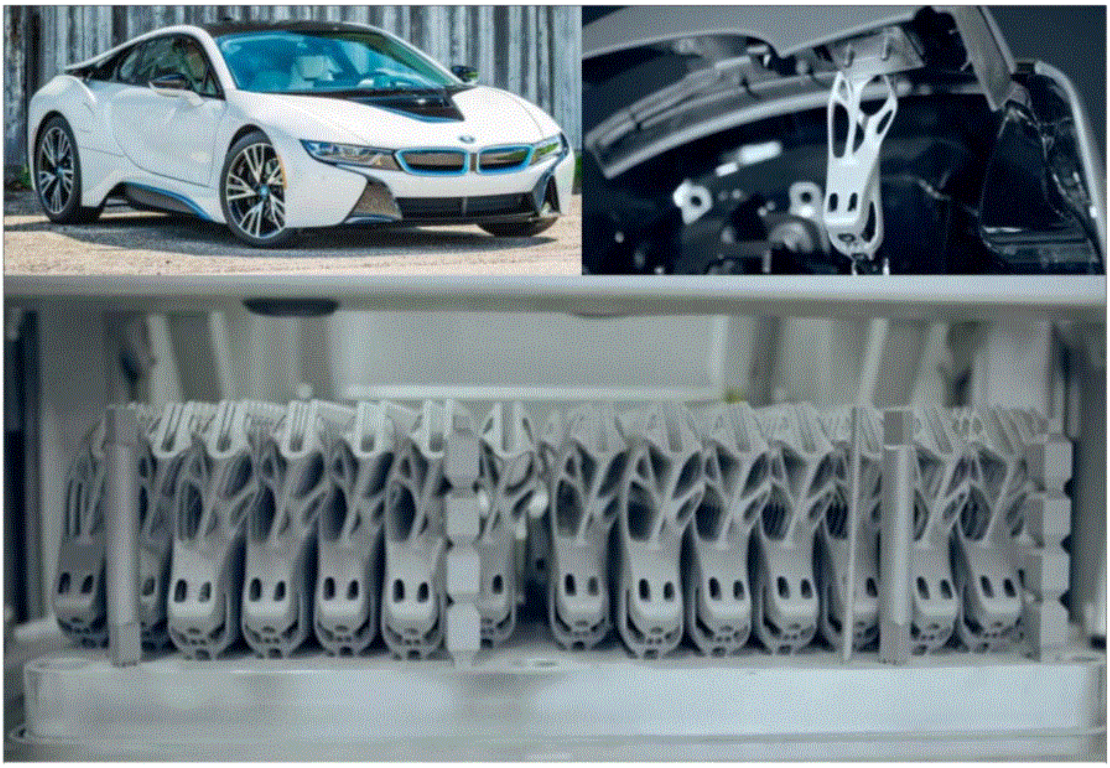


Figure 19: The case of the BMW i8 Roadster

Probably, Bugatti is the greatest example of functional lightweight components, combining parts consolidation and functional integration. In 2018 they presented a world premiere: an additively manufactured optimized brake caliper made of titanium alloy, providing 40% weight reduction and high temperature strength.

Figure 20: Bugatti’s titanium brake caliper

Currently, structures development is focusing on chassis functional design, with structural joints to sustain light and modular design, or metal deposition for body reinforcement or parts remanufacturing [Josten 2020, Edag]. Moreover, AM of composites is growing, with the development of carbon fiber and composite fixtures or even monocoque framesets. The American Arevo is the example of the first additively manufactured monocoque framesets for bikes that achieves high customized production [Arevo]. Nowadays, we can even find applications in drivetrain and powertrain, besides many research case studies and prototypes.

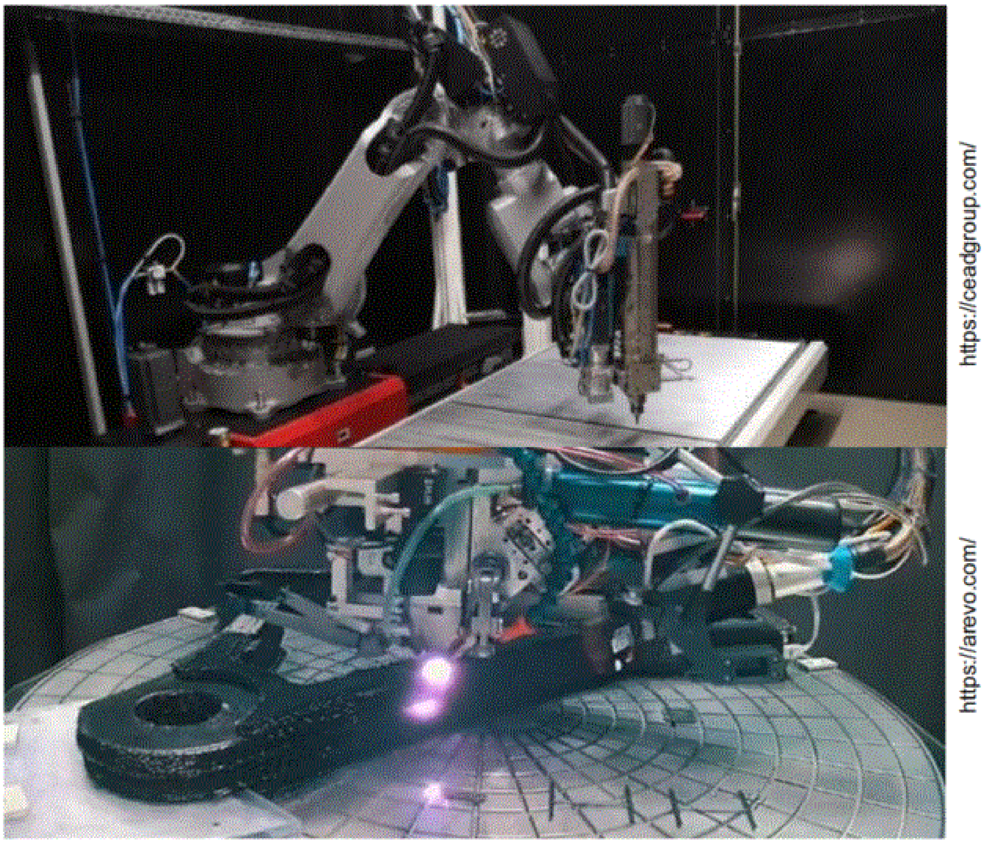


Figure 21: Additive Manufacturing of composites structures [Cead, Arevo]

From the lightweight and high-efficiency engine concept of FEV, to the prototype integrated housing for electric motor, gearbox, and heat exchanger of Porsche, to the end-use exhaust manifolds of Scuderia Ferrari.

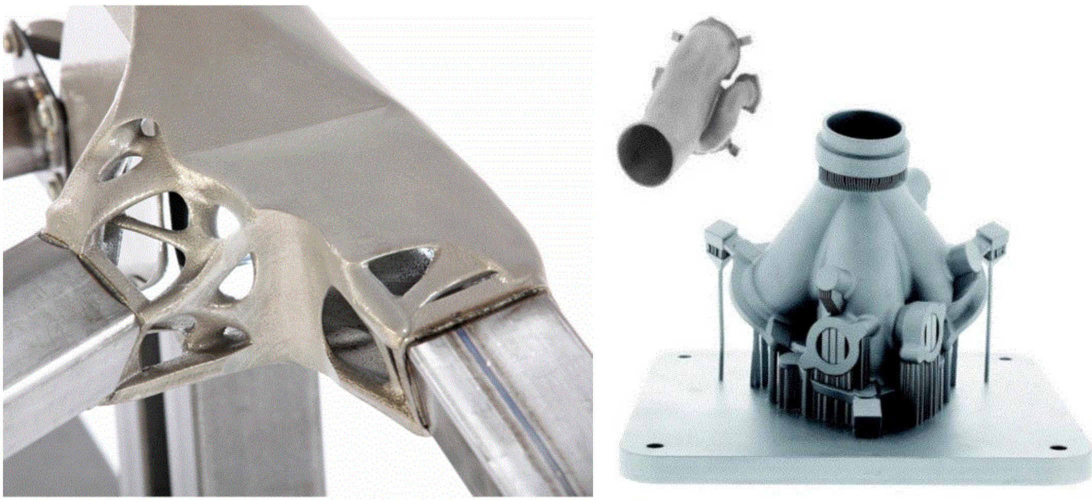


Figure 22: An alluminum chassis joint and a Ferrari engine component

Or, finally, the pistons for the high-performance engine of the GT2 RS. In 2020, Porsche established a new milestone for the production of additively manufactured high stressed drive components, integrating lightweight design and functional internal cooling channels. A comprehensive review of additively manufactured internal combustion engine (ICE) components is provided by Gray et al. [Gray 2020].

Figure 23: The engine piston for the GT2 RS

1.3.2 Further implications

As introduced before, the adoption of AM in industrial settings such as the Automotive has huge impacts not only on product innovation, but also on production, logistics, environment, and green transition. Recent research is therefore focusing on those implications in the forthcoming scenario. Bockin et al firstly performed an environmental assessment of AM adoption in the automotive [Bockin 2019]. In fact, this will be a central topic for the sector in the forthcoming years. They concluded that studies are needed to quantify the potential environmental consequences from spare part printing, but also different logics of facilitated dismantling, integration of components, material choice, reduced material waste, and post-processing. Of course, AM can minimize storage of both spare parts, and tooling, therefore, it can lead to enhanced business models due to the supply chain shortening and the overall lead time reduction. Delic et al. analyzed the contribution of AM adoption in production processes to the flexibility and performance of the automotive supply chain management [Delic 2020]. The empirical findings showed that Additive Manufacturing adoption has a direct positive impact on the automotive supply chain flexibility, which, in turn, positively influences the supply chain performance. Sanchez et al., by analyzing the Spain market and spare parts printing, concluded that it would be possible to improve the industrial margin of automobile spare parts business activities while decreasing the environmental impact [Isasi-Sanchez 2020]. Llopis et al. state that trends in automotive production such as electric mobility have further made AM an interesting and viable option for the development of integrated and functional parts [Llopis 2021]. Charles et al. analyzed the automotive industry and the potential for driving the green and electric transition, concluding that AM technologies have the potential to improve the efficiency of automobiles, which is fundamental for fuel efficiency and range of electric cars [Charles 2022]. To conclude, on the side of the product, fuel efficiency and emissions trends benefit from functional integration and lightweight AM design. Advantages can be even found in production and logistics through AM parts production and relative supply chain. Further studies are needed about on-demand production and manufacturing materials and energy management.

2 Methodology and tools: State of the art

2.1 The Research Landscape

Considering the trends presented in Chapter 1, AM technologies and relative applications are continuously evolving. Both research and industry actually drive the developments, which can be encased in four main topics, according to recent reviews. Schmidtt et al. [Schmidtt 2021] depicted the research landscape, by identifying the domain of market and application as a field shared by the four main categories created by the EPO in 2020 [Ceulemans 2020].

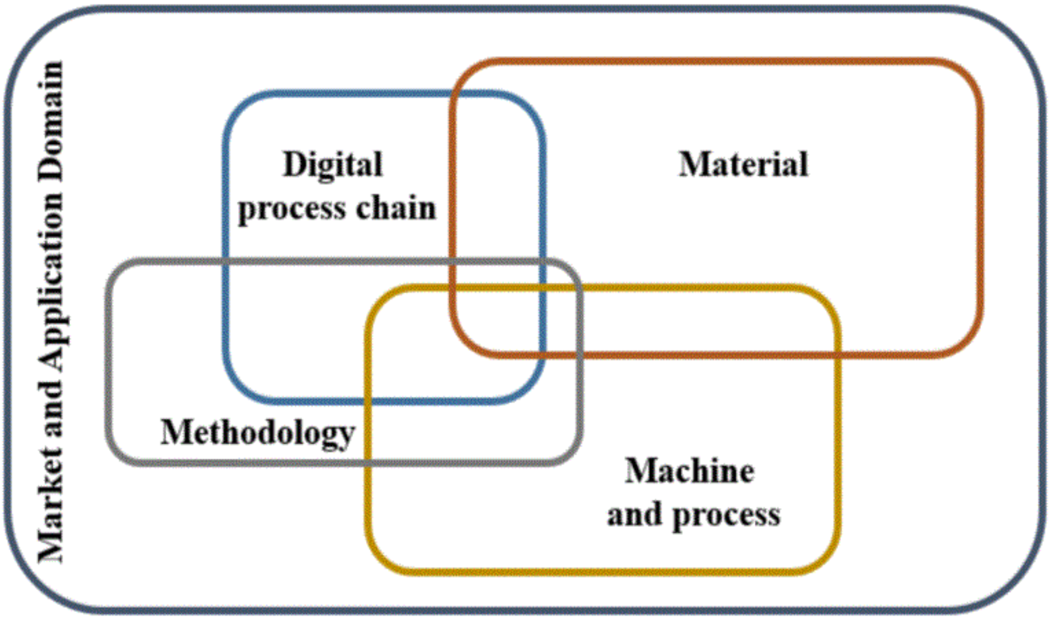


Figure 1: The Additive Manufacturing research landscape [Schmidtt 2021]

Therefore, the four categories are:

- Machine and processes
- Material
- Digital process chain
- Methodology

Afterward, the study deepens the four categories to understand the relative topics, finding also that 80% of the AM scientific publications have been written in the last 10 years. By analyzing this type of study, we can understand that applications are constantly increasing, and there is a lot of vertical research in specific areas, in particular on processes and materials. The digital process chain, including research aspects related to digitized manufacturing and the handling of the digital representation of the product, are also important, intending to facilitate the spread of the “digital twins”. The AM-related knowledge effects on the product development process are instead the core of methodology. It is acknowledged that the development of knowledge, but also tools, rules, guidelines, workflows, and methodologies in general is one of the technical principal challenges of AM [Thompson 2016]. For the purpose of this work, we are going to deepen what Design for Additive Manufacturing means and what is the state of art, to identify the research gap.

2.2 Design for Additive Manufacturing

What does Design for Additive Manufacturing (DfAM) mean? Of course, we are speaking about specific knowledge that is addressed to support AM. Taking one step further, we can imagine DfAM as the whole set of approaches to transform the revolutionary potentials of AM, mentioned in Chapter 1, into real applications and effective benefits. In fact, in a recent review, Vaneker et al. reported that the lack of (structured) knowledge on DfAM has been identified as one of the barriers that hold back further adoption of AM in the industry [Vaneker 2020].

2.2.1 Roadmap of DfAM

Actually, we can consider DfAM from different perspectives. The first mention, contemporary to the AM establishment at the standard level, dates back to 2009 when Bourell suggested developing new design methodologies dedicated to AM and inspired by Design for Manufacturing and Design for Assembly [Bourell 2009]. Afterward, in 2010 Gibson defined DfAM as a methodology to “maximize product performance through the synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to the capabilities of AM technologies” [Gibson 2010]. From those early definitions, it is clear that DfAM can be intended at different levels, specifically for different purposes, providing different implications. Thus, researchers started to classify the studies on DfAM methodologies. In 2014 Laverne et al. distinguished DfAM for concept assessment and DfAM for decision making [Laverne

2014]. Considering the first, qualitative and quantitative approaches could be respectively distributed along the design process, but they finally end up among the methodologies for choosing an AM technology. Considering the last, they could be classified into Guidelines, DfAM for product properties, DfAM for design optimization, DfAM for geometrical validation, thereby creating correspondence to the stages of the design process. In 2016 Kumke et al. defined a further classification, considering DfAM in the strict sense and DfAM in the broad sense and, moreover, provided a proposal for a DfAM framework [Kumke 2016].

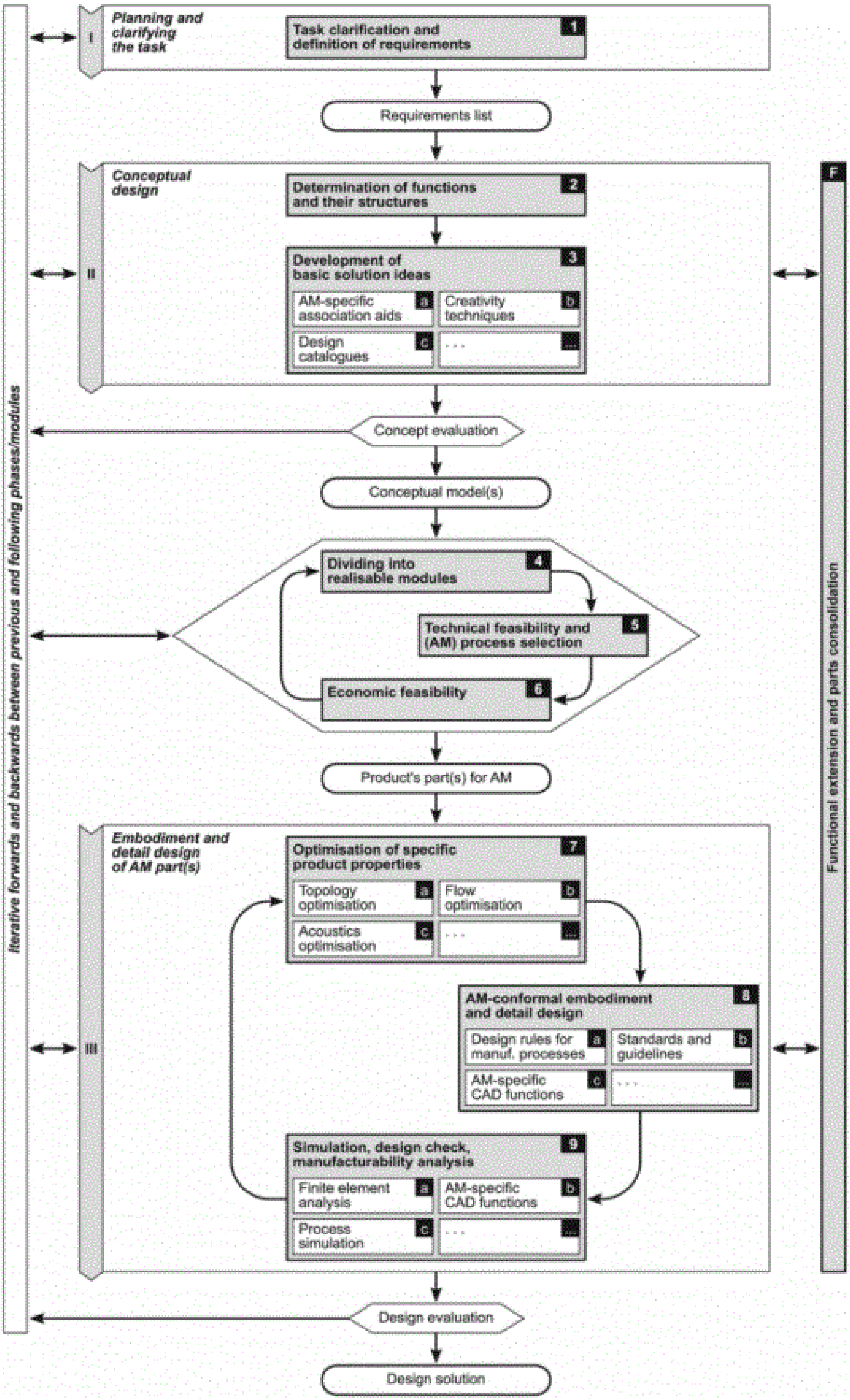


Figure 2: The DfAM framework proposed by Kumke et al.

Thus, DfAM in the strict sense included design rules, utilization of AM potentials, and also combined approaches and methodologies. Conversely, DfAM in the broad sense could be related to process selection and production strategy, selection of parts/applications, and manufacturability analysis. Instead, the DfAM framework could be based on the VDI 2221 process model, related therefore to the established subdivision into the phases of planning and task clarification, conceptual design, embodiment design, and detail design. Nevertheless, the framework focuses only on the product design phase. In 2016, Thompson et al. provided a review on DfAM, representing a milestone in the field, where it started emerging the centrality of the topic. Again, DfAM could be seen as a subset of Design for Manufacture and Assembly or, in a wider perspective, as a subset of Design for X. But in this case, it has been viewed from three levels of abstraction. Thompson et al. concluded that “insufficient understanding and application of DfAM was said to be limiting the overall penetration of AM in industry, holding back the use of AM for the production of end-use parts, preventing designers from fully benefitting from AM, and preventing AM from reaching its full potential in general” [Thompson 2016]. More lately, in 2018 Pradel et al. distinguished DfAM approaches into heuristics, principles, guidelines, rules, process guidelines, specifications, and process selection tools, along the design process [Pradel 2018]. The framework considered the general design steps, however, it was subdivided into design and manufacture. Thus, also process programming was identified as a key phase considering as well manufacturing and post-processing operations. In 2019, Wiberg et al. reviewed DfAM methods and tools and depicted a research framework based on three main sequential phases, which are system design, part design, and process design [Wiberg 2019].

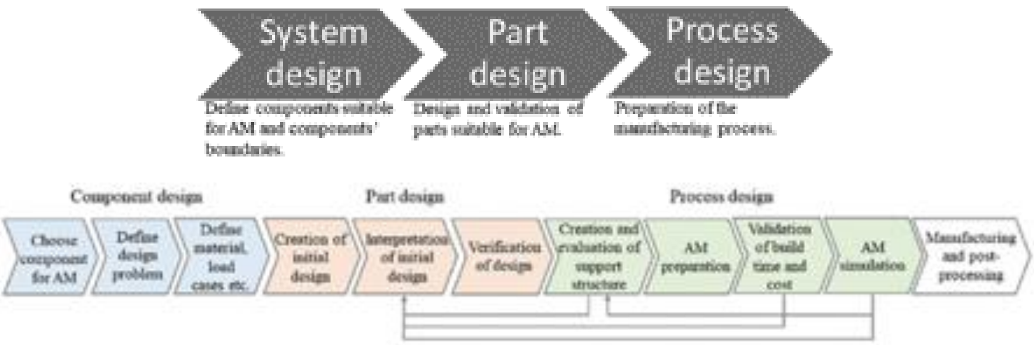


Figure 3: The DfAM framework proposed by Wiberg et al.

In this case, the first, similarly to the product planning step is to define the design boundaries, the subsequent is related to product design, while the last is the process design. From this perspective, DfAM starts to be considered as a workflow that can be optimized. The study concludes that for this purpose, not only systematic knowledge but also integration and automation are needed. In 2020, Vaneker et al. provided a last review on DfAM, maintaining the subdivision in the three main steps, but detailing the operations required in order to optimize product and process design [Vaneker 2020].

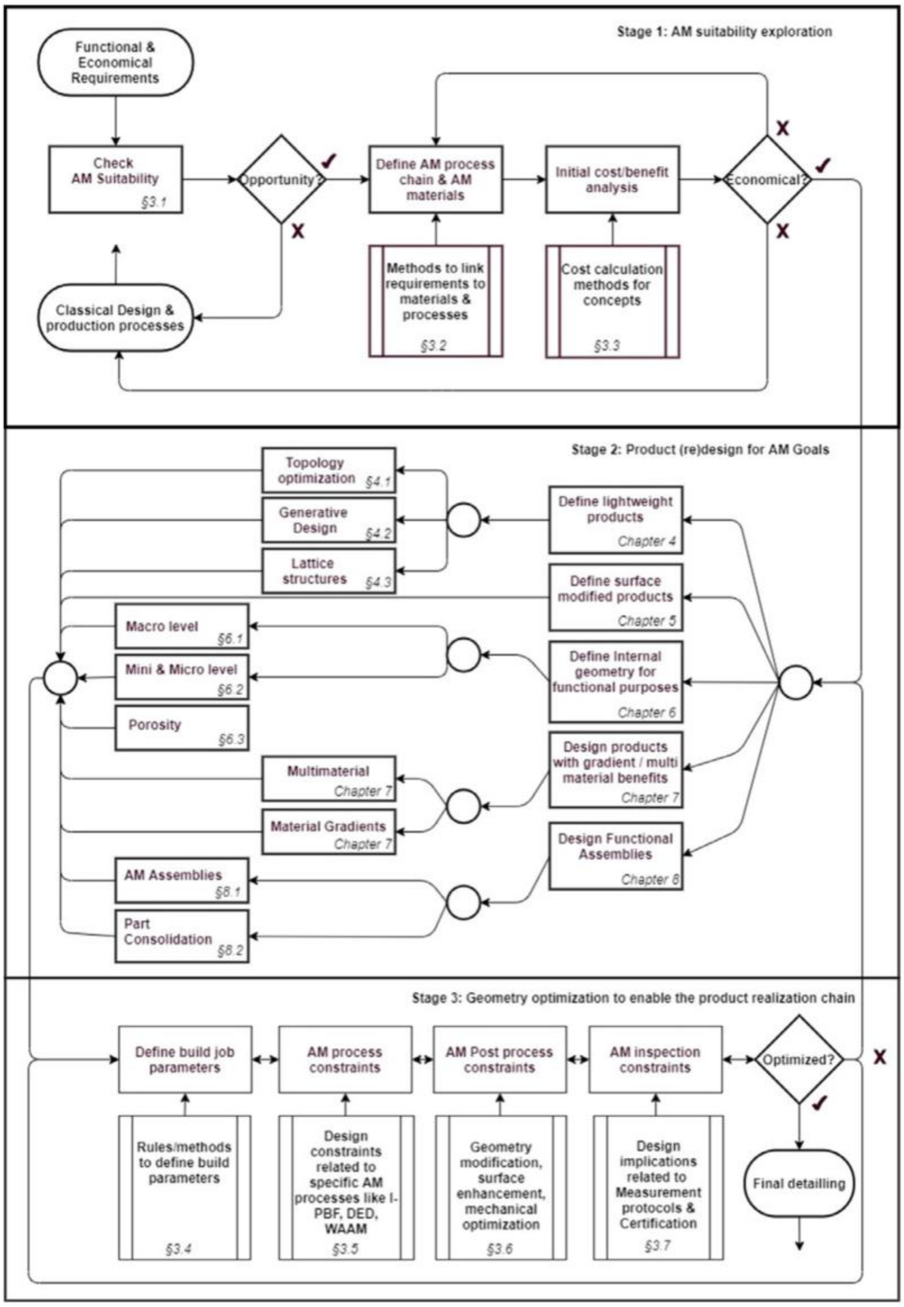


Figure 4: The DfAM framework proposed by Vaneker et al.

The study concludes that the development of methods and design tools is still a matter of basic research. In particular, “integrating processing and manufacturing with design in AM is feasible since the full digital chain is there (…) and a combination of computational and knowledge-based methods would be an optimal solution for DfAM in the future to define qualified AM design solutions”.

We can conclude, from what was stated before, that is fundamental to understand the disruptive capabilities of AM and to translate them into actual benefits by developing approaches that effectively integrate product and process design and efficiently address designers’ intent. The rest of the chapter deepens DfAM, retrieving AM capabilities and introducing key points of product design and process design. Moreover, computer-based tools to support DfAM are introduced as well and, finally, the research gap and the objectives of this thesis are explained.

2.2.2 Design methodologies and DfAM

“If you call it, ‘It’s a Good Idea To Do’, I like it very much; if you call it a ‘Method’, I like it but I’m beginning to get turned off; if you call it a ‘Methodology’, I just don`t want to talk about it”

(Alexander, 1971)

In the late 70s, Boothroyd and Dewhurst started studying assembly operations and the related time needed to understand the design changes that can lead to cost reduction. Their findings were then identified as Design for Assembly (DfA). In the late 80s, Stoll started to consider simultaneously products and production to understand the objectives and constraints of design and manufacturing. His findings led the way for Design for Manufacturing (DfM). Implementation of both DfA and DfM approaches provided important benefits in product development, such as simplification of products, reduction of assembly and manufacturing costs, improvement of quality, and reduction of time to market [Kuo 2001]. Afterward, from the 90s, product development evolved thanks to the spread of computer-aided tools and simulation. That led to the spread of the Concurrent Engineering (CE) approach, which substituted the sequential design approach (“throw over the wall”) with parallel processing of activities [Sohlenius 1992], to improve the design efficiency and cut the design lead time.

According to Gibson et al, Design for Manufacture and Assembly (DfMA) [Boothroyd 2011] approaches efforts can include [Gibson 2010]:

- Industry practices, including reorganization of product development using integrated product teams, concurrent engineering, and the like
- Collections of DFMA rules and practices
- University research in DFMA methods, tools, and environments

However, they can be viewed from different levels of abstraction [Thompson 2016].

At the first level DfMA guidelines, can be:

- process-specific,
- feature-specific
- activity-specific

They can be therefore distinguished considering respectively the manufacturing processes involved, the geometrical features of the components, and the required operations of a process flow.

At the second level, DfMA aims to understand and quantify the effect of the design process on manufacturing (and vice versa), and, thus, they can improve the manufacturing system.

At the highest level, DfMA explores the relationship between design and manufacturing and its impact on the designer, the design process, and design practice.

Thus, one step forward, depending on the aspect it is aimed to improve, it can be considered as a subset of Design for X (DfX). In fact, Design for X is a “generic name for the members of a family of methodologies adopted to improve design product as well as design process from a particular perspective which is represented by X” [Tomiyama 2009]. DFX implies the earliest consideration of design objectives and their constraints as well as capitalization and dissemination of knowledge [Huang, 1996].

Design for Additive Manufacturing can be therefore considered as

- DfMA guidelines related to the Additive Manufacturing processes
- DfMA rules specific for the Additive Manufacturing processes
- DfX approaches to improve the Additive Manufacturing system

Anyhow, the design knowledge, processes, and tools are substantially different from traditional technologies, and thus AM-specific design rules and tools must be developed since, as stated before, systematic approaches are fundamental for the AM widespread in industry.

2.2.3 DfAM Design Guidelines

In order to introduce the general design guidelines, we have to consider the disruptive design capabilities of AM, by deepening the concept of "design freedom" mentioned in Chapter 1.

The ISO/ASTM 52910:2018 "Additive manufacturing — Design — Requirements, guidelines and recommendations" standard helps us for this purpose, by resuming the design key points for product optimization [ISO 52910]:

- Part customization
- Lightweighting
- Use of internal channels or structures
- Functional integration
- The use of designed surface structures
- The use of multi-material or gradient material parts

Starting from those points, we can consider general guidelines, such as the few interesting examples provided by Gibson [Gibson 2010]:

- AM enables the usage of complex geometry in achieving design goals without incurring time or cost penalties compared with simple geometry.

- As a corollary to the first guideline, it is often possible to consolidate parts, integrating features into more complex parts and avoiding assembly issues.
- AM enables the usage of customized geometry and parts by direct production from 3D data.
- With the emergence of commercial multimaterial AM machines, designers should explore multifunctional part designs that combine geometric and material complexity capabilities.
- AM allows designers to ignore all of the constraints imposed by conventional manufacturing processes (although AM-specific constraints might be imposed).

2.2.4 DfAM Design Rules

In order to provide examples of design rules, it is necessary to introduce the general AM process steps. From this perspective, all the steps are common between the AM technologies. Specific processes will require proper design and manufacturing considerations.

Vaneker et al. explain that the process of creating an additively manufactured product can

be subdevided into seven steps [Vaneker 2020]:

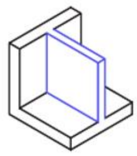
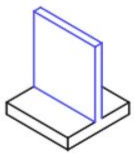
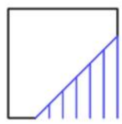
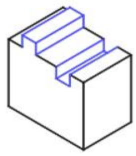
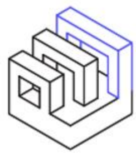
- Model design
- STL file creation
- Build preparation
- The build process
- Part removal and post-processing
- Quality and inspection
- Application

Model design can be obtained either by 3D capturing reverse engineering, CAD 3D direct modelling, or via a shared database on the cloud. The model is generally converted into an STL file (even though specific formats for AM such as AMF, 3MF, etc., do exist), which is a tessellated representation of the object. The STL is processed in the build preparation step, where it is manipulated and instantiated by defining the orientation, the position, and the required support structures to return the build job. Moreover, machine parameters are set up (e.g. scan paths, speeds, temperatures, etc.) and the slicing is computed and converted into an NC code for the AM machine. Once the manufacturing process is finished, generally the part is in a raw state, therefore it requires further post-processing steps. Most common are parts removal, supports removal, thermal treatments (e.g. annealing, sintering, curing, etc.), and functional surfaces finishing (e.g. machining, sandblasting, polishing, etc.). Finally, parts can pass through quality control and can be ready for actual applications.

Considering specific design rules, Alfaify et al. provide a synthesis of most common ones [Alfaify 2020]:

- The inclination angles of overhang parts should be greater than a given lower bound angle
- Self-supporting angle varies depending on the material, but it is typically around 45 degrees
- Overhang with small inclination angle can make removal of the supports difficult.
- Removal of the support structure greatly reduces the surface finish and requires post-processing
- Hollowing out parts (if functionally accepted) leads to reduced printing time and material utilization
- Interlocking features can be used to link parts in cases of assembly difficulties or large parts are required to be divided as AM has limited building space
- For post-processing, the machining allowance should be considered when dimensional accuracy is required. etc.

An example of a synthesis of DfAM design rules for PBF processes is depicted in Figure 5.

	Supported walls	**Unsupported walls**	**Support & overhangs**	**Embossed & engraved details**	**Horizontal bridges**
	Walls that are connected to the rest of the print on at least two sides.	Unsupported walls are connected to the rest of the print on less than two sides.	The maximum angle a wall can be printed at without requiring support.	Features on the model that are raised or recessed below the model surface.	The span a technology can print without the need for support.
					
Direct metal Laser sintering	0.4 mm	0.5 mm	support always required	0.1 mm wide & high	2 mm

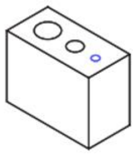
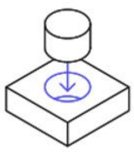
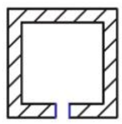
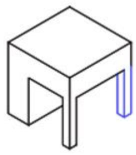
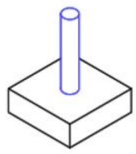
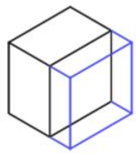
Holes	**Connecting /moving parts**	**Escape holes**	**Minimum features**	**Pin diameter**	**Tolerance**
The minimum diameter a technology can successfully print a hole.	The recommended clearance between two moving or connecting parts.	The minimum diameter of escape holes to allow for the removal of build material.	The recommended minimum size of a feature to ensure it will not fail to print.	The minimum diameter a pin can be printed at.	The expected tolerance (dimensional accuracy) of a specific technology.
					
Ø1.5 mm		5 mm	0.6 mm	1 mm	±0.1 mm

Figure 5: L-PBF design rules [3DHubs]

2.2.5 DfAM Design Approaches

In order to deal with approaches, whose perimeter is the whole design process, it is appropriate to introduce the DfAM workflow. As cited before and confirmed by literature [Pradel 2018, Wiberg 2019, Vaneker 2020], we can subdivide the workflow into three main phases:

- Product planning
- Product design
- Process design

The first phase is Product Planning, which includes several activities such as data collection, feasibility studies, preliminary analyses, and the definition of projects objectives and constraints. Subsequently, the Product design phase can start, with the aim to maximize product performance and thus to optimize its design considering the AM process. Afterward, Process design is required, including build preparation to create the job, and eventual process simulation. Finally, the production can start, with product printing and related post-processing and control steps as necessary.

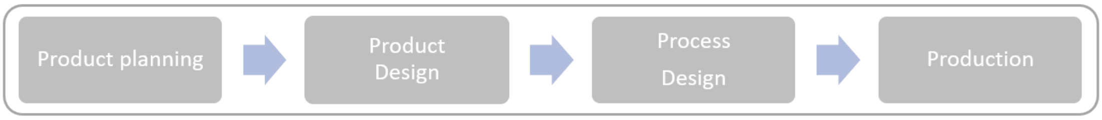


Figure 6: A general DfAM approach

In fact, Pradel et al. divided the DfAM framework into Design and Manufacturing, incorporating the Requirements step (i.e. AM material and process selection) in the Design and considering production as output. Conversely, Wiberg et al. identified the first step of the DfAM process as the System Design (i.e. parts, process, and material selection), followed by the Part Design and the Process Design, and the production is output as well. Vaneker et al. proposed three design stages for DfAM, the first to select part and technology candidates, the second to achieve product optimization, and the third to achieve process optimization. Again, the production is the subsequent phase outside the boundaries. Starting from those analyses of the state of the art and considering a general process flow, we can observe that the fundamental steps are the model design and the build preparation. Those steps are directly connected to

Product design and Process design, and, in the DfAM viewpoint, they can be respectively aimed to achieve Product optimization and Process optimization. DfAM entails that the effects of design on manufacturing and vice-versa have to be taken into account to optimize product performance and quality minimizing development and production time and costs. DfAM approaches can succeed by providing concurrent Product and Process optimization.

Product design and Process design approaches are going to be introduced, as well as the proper computer-based tools through which they be implemented. In order to explain the key elements of product and process design in DfAM for the purpose of this thesis, we consider the case of lightweighting, which is one of the most important trends in the automotive sector.

2.3 Product Design

Product design aims to maximize product performance by exploiting the design freedom offered by AM. In order to do that, we can speak about product optimization, according to functional requirements and process-specific AM constraints. Form freedom related to technology implementation let fully re-thinking objects whose design underwent approach methods to freeze due to traditional constraints of manufacturing and assembly [Boothroyd 2011]. The possibility to produce a combination of organic elements, lattice elements, hollow elements, and variable density infills, let new developments in functional design [Milewski 2017]. All these techniques can be exploited and combined in order to perform design optimization. Some advantages of these methods, together with innovative metallic alloy use, are the possibility to obtain extremely light structures.

Among the functional design potentials reported in the ISO/ASTM 52910:2018 that have been previously introduced, lightweighting can be one of the aims of product optimization [ISO 52910].

2.3.1 Lightweight functional design

One of the aims of structures design is the minimization of mass and maximization of material usage efficiency, thus lightweight design has always been a core focus of the engineering field. Generally, implementation of lightweight design leads to the high complexity of geometries and thus it has always been hindered by traditional manufacturing technologies. Nature provides several examples of lightweight structures with different functional aims [du Plessis 2019]: branched shapes of plants and bones tissues are not only to bring loads but also to let biological fluids flow. Most of them have local optimization as well since bones' porosity or plants' stem channels decrease moving to outer regions in order to improve bending and torsional stiffness. Honeycomb structures is another example of high stiffness and extreme volume-mass ratio, with the best compromise between functional inner space and material usage. Generally, human structures design leads to simplified geometries, since it is constrained by manufacturing and assembly feasibility. Concurrent engineering approaches based on Computer-aided technologies (CAX) involve design and simulation iterations to achieve structural and functional targets and subsequent redesign for industrialization, introducing process constraints. Additive Manufacturing (AM) implementation lets rethink features of shapes and geometries in order to exploit the Functional Design and thus making the design driven by engineering specifics instead of production constraints. The two main strategies for the design of lightweight structural optimized parts to be produced by Additive Manufacturing are cellular structures design, or rather Latticing, and Topology Optimization. Moreover, we can currently consider the third approach, which is Generative design. While the former can be considered as an Expertise-driven process, Topology Optimization can be structured as a Mathematically-driven process [Plocher 2019], since it can be linked to a numerical function optimization problem. From a structural point of view, structural optimization can actually involve different approaches. Size or parametric and shape optimization work on thickness distribution and deformations superposition. Topography, Topometry and Topology Optimizations work respectively on bead patterns, thickness distribution and material distribution A consolidated and effective approach in advanced settings is based on a combination of results of different kinds of optimization in sequential steps for the design of lightweight structures [Cavazzuti 2011]. Topology Optimization allows to obtain improved solutions for structures with non-conventional shapes, but just Additive Manufacturing has actually bridged the gap between design and manufacturing, allowing to unlock its potential for practical applications [Brackett, 2011; Zegard 2016]. Indeed, a shape with organic and branched aspects computed through Topology Optimization is a good way to implement Functional Design, exploiting the design freedom induced by AM [Meng 2020]. Its results generally present shapes that a traditional design process cannot visualize and this, summed to the possibility to obtain lighter structures without going through several trial and error processes, allow the designer to have much more creative possibility with less time spent. Therefore, due to its capability to understand the optimal distribution of the material in advance, it is an interesting method applicable from the earliest design step to cut down the design time.

To summarize, the product optimization strategies for lightweighting are therefore:

- Topology optimization
- Latticing (lattice structures)
- Generative design

Vaneker et al. recently well synthesized the approaches working and application [Vaneker 2020]. Therefore, we are going to introduce the three approaches, providing for each a related application example from literature.

2.3.2.1 Topology optimization

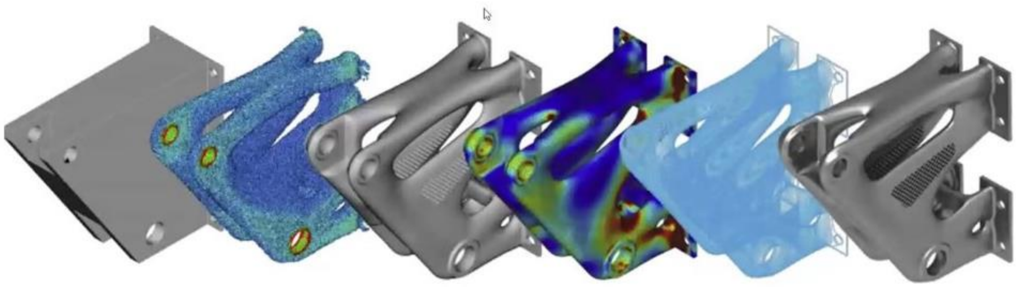


Figure 7: A topology optimization workflow

It is a mathematical approach that optimizes the material layout within a given design space, for a given set of loads and boundary conditions such that the resulting layout meets a prescribed set of performance targets. It is a numerical method to effectively distribute material into a control volume, aiming at maximizing or minimizing specific criteria (e.g. weight, stiffness, thermal conductivity, resonance frequency, etc.), according to set constraints. For this purpose, different objective functions can be used in a numerical maximization (or minimization) problem and different solving algorithms can be adopted as well. Moreover, the constraints that can be introduced in the numerical problem can have a huge impact on topology results. Further details will be given later.

Example

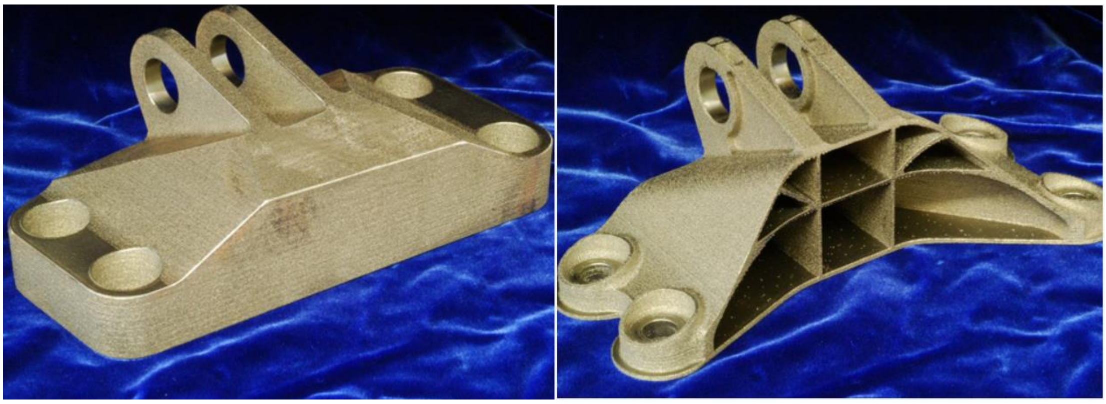


Figure 8: The GE design challenge: on the left, the original component; on the right, the winning design from M. Arie Kurniawan

An acknowledged 'design for additive' application in literature is the case of the General Electric (GE) bracket for a jet engine [Morgan 2016]. In 2013 GE launched a design challenge on the GrabCAD website [Grabcad], with the aim to develop an optimized variant that minimized the mass of the existing aviation component. The challenge obtained more than 700 applications, and the 10 finalists received $1,000 each, while the best design proposed by M. Arie Kurniawan was awarded $7,000 in prize money [General Electric]. The original bracket weighed 2.033 kg, while the winning design just 0.327 kg, providing an impressive 80 mass reduction. The case study thus became one of the most famous applications of lightweight design, and many studies are still focused on its development working on the improvement of design optimization methods. Figure 8 depicts the original and the awarded design, while figure 9 reports a design achieved by topology optimization provided by 3DSystems (PTC's Frustum software) [3D Systems]. That design cut the aircraft bracket by 70% while meeting all the structural requirements.

Figure 9: A topology optimization example of the GE bracket

2.3.1.2 Generative design

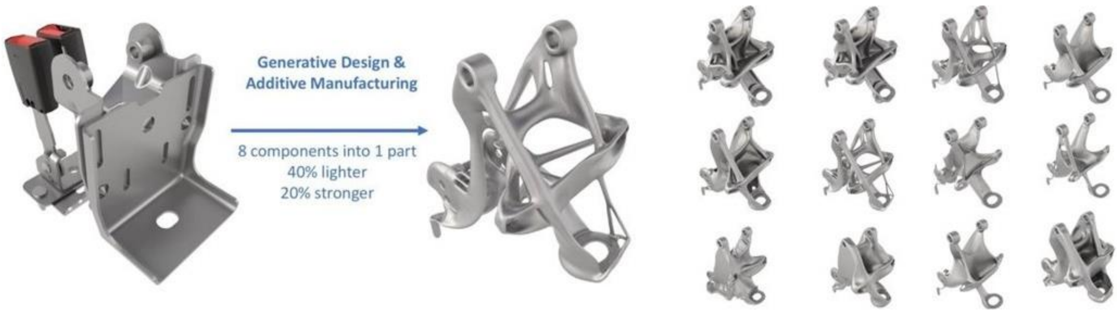


Figure 10: A generative design workflow

Since it is very difficult to find a unique optimal design by setting a topology optimization, automatized processes are being created to ease the design exploration. Practically, it is probable to obtain many local optimum results, and the possible optimal solutions belong to a Pareto front. Vaneker states that “a compromise should be made to sample the solution space when the theoretical global optimal could not be located” [Vaneker 2020]. Generative Design applies a generative system to perform that design exploration phase. For this purpose, multi-objective topology optimizations are set up and return a population of design variants. Currently, it is difficult to define proper variants selection criteria and there is room for the development of proper constraints to consider the AM process and postprocessing issues.

Example

Figure 11: A generative design example of the GE bracket

Considering the case of the GE bracket, the optimized example provided by Siemens [Siemens] using generative design is depicted in figure 11. The redesign achieved a 75% mass reduction, while keeping the structural safety targets.

2.3.1.3 Latticing

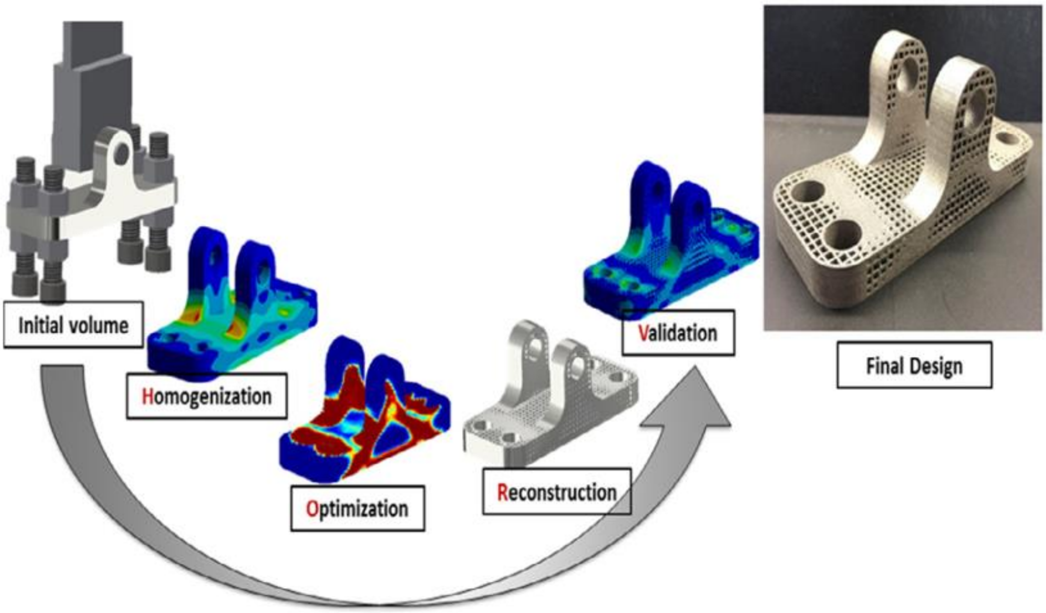


Figure 12: A latticing workflow

Lattice structures design is based on the definition of cellular structures that are distributed within a given design space. Solid volumes are therefore replaced by lattices or porous geometries that present specifically designed features and provide an equivalent density lower than the bulk material. Vaneker defines latticing as "another way of compromising by approximating the optimal design solution". In fact, most topology optimization algorithms are based on density thresholds to define the material distribution, but actually, functional design can be based also on intermediate-density distribution. As stated before, it is often an expertise-driven design, based on previous structural analysis or topology optimization setup. Generally, lattice structures are stored in libraries and then they are managed through parameters to fill the design space. Even for this approach, there is room for development concerning actual lattice behavior and manufacturability.

Example

Figure 13: A latticing example of the GE bracket

Considering the case of the GE bracket, two improved examples provided at Siemens [Siemens] (Fig) and at Fathom by Porterfield (Rhyno's Crystallon software) [Blog Rhino] (fig) using lattice structures are depicted in figure 13. Instead of simply replacing the bulk material with lattice, there is no shortage of examples of part optimization based on advanced methods, as in the case of Opgenoord et al. [Opgenoord 2019], that provided a design with nearly 80% weight reduction.

2.3.2 Topology optimization

For the purpose of this thesis, we are going to deepen topology optimization techniques, since they can represent the most relevant in the DfAM context. Moreover, they will be considered the key step to achieve product optimization in the design phase of the methodology that will be proposed.

TO definition dates back to the early twentieth century [Rozvany 2009]. Its first computational application contributions are due to [Bendsoe 88] in the eighties; nevertheless, its full application in real cases has always been hindered by design software and technological constraints. TO is a numerical method to effectively distribute material into a control volume, which aims to maximize or minimize specific criteria (e.g., weight, stiffness, thermal conductivity, resonance frequency) according to set constraints. In applications for lightweight design, specific design tools for TO can be used to obtain a lighter structure for a set stiffness or to minimize its compliance with a given target mass. Nowadays, many algorithm categories have been developed to solve a TO problem [Zuo 2007]. The most prominent ones have been classified and described by Sigmund et al.: Density-based; Level Set Evolutionary/Genetic Algorithms; Topological Derivatives and Phase Field [Sigmund 2013]. Most widely used [Rozvany 2009] are homogenization density-based methods such as the Solid Isotropic Material with Penalization (SIMP), even though several research works concern the Evolutionary Structural Optimization (ESO) development, mainly in its more known Bi-dimensional version (BESO). The SIMP method is actually the most implemented algorithm in commercial software [Reddy 2016], due to its computational efficiency and its ability to generate excellent results in terms of mechanical performance and aesthetics. A lot of research effort has been contributing to the development of the algorithm adding features suitable in industrial applications in real cases [Gardan 2016, Liu 2018]. Moreover, technological and manufacturing features have also been involved, such as constraints for machining [Zuo 2006] or casting [Harzheim 2006]. The last decade highlights increased interest in the improvement of AM technologies [Plocher 2016], which opened new challenges for the development of design methods and tools.

Figure 14: The effect of process constraints on topology optimization

2.3.2.1 Topology optimization workflow

We can refer to the subdivision of the DfAM workflow into three main phases:

- Product planning
- Product design
- Process design

Indeed, for lightweighting guideline purpose, topology optimization can be considered as the key step to achieve product optimization in the product design phase. In turn, to implement topology optimization, we can define a workflow related to industrial and academic practices in development of applications.

Therefore, the steps that compose a topology optimization workflow are:

- Geometry preparation
- Optimization setting
- Results and Post-processing.

In order to perform a topology optimization of a product by using proper design tools, the sequence of tasks that are included in the workflow is now described.

Geometry preparation.

The first phase aims to create the 3D geometries to be used to compute a TO by means of CAD tools. The first step can be the direct model import of the original non-optimized part, or the retrieve of elements required as boundary conditions, related to the assembly where the part has to fit and work. Subsequently, the Design Space, or rather the volume set for shape computation, must be created. According to geometrical constraints, it must be as large as possible, so that the material distribution can be calculated with maximum freedom. A Non-Design Space is required as well to define the forbidden volumes for shape computation, since they must be kept for functional reasons. Moreover, a key step is the material definition for further model simulation.

Optimization setting.

The aforesaid 3D geometries need to be discretized by creating a finite element model. The first step is mesh generation, selecting the type and size of elements and introducing the required refinements. Afterwards, in order to simulate product physical behavior, proper sets of loads and restraints need to be created and applied to the model. Finally, the optimization can be set up, including at least one target and one constraint. Moreover, implemented manufacturing constraints and geometrical constraints can be included, as well as the opportunity to interact with algorithm solving by additional settings made available by user interfaces. Solving parameters may also be specified for the iterative computation.

Results and Post-processing.

Once a result has been obtained, in general, the possibility to visualize it and analyze it should be granted. A basic finite element analysis of the computed model can be provided, or a geometry generation can be preliminarily required. This output can be automatically created by the design tools; conversely, in the worst case, no data about the computed result are provided. In this latter instance, firstly a manual geometry interpretation by CAD modelling is necessary and finally, a finite element analysis of the new model can be performed. A key point is the possibility to manipulate the geometry for results displaying, design modification, or further simulations.

2.3.2.2 Topology Optimization Issues

Current issues and possible developments can be encased in two main areas:

- TO algorithms and tools and features development;

- TO workflow and DfAM effectiveness.

The first point concerns TO usability improvements, such as support-free structures [Gaynor 2014, Leary 2014], optimization of supports [Mezzadri 2018], or both supports and part orientation [Langlelaar 2018]. Currently, a lot of studies are focused on performance maximization subject to support structure constraints [Mirzendehdel 2016]. Nowadays, many Computer-Aided Engineering (CAE) tools implemented TO so that it can be exploited by AM technologies [Meng 2020]. Reddy et al. [Reddy 2016] realized their importance and attempted to benchmark commercial and academic available software. Most current design tools still show room for the development of specific AM constraints. Self-supporting structures [Hoffarth 2017], material anisotropy [Zhang 2017] introduction and implementation [Liu 2018] are interesting advances. However, build direction still cannot be computed aiming to minimize supports, build time, or part warping [Reddy 2016], and other challenges concern functionally graded structures and materials, or TO and lattices integration [Cheng 2019, Dong 2020], as confirmed by recent reviews [Zhu 2021]. The second point regards the process chain and the integration within DfAM methods. Workflow steps can be complex and slow and manual design interpretation is time-consuming [Lindemann 2015] and could benefit from smooth boundary representation to get “ready to print” models [wiberg], but currently, as Reddy et al. [Reddy 2016(b)] explain, designers have to interpret design and add further studies taking into account build direction, overhangs, supports and build time by using additional design tools and personal experience. Integration of specific design tools in the design phase could be a great advantage to improve the DfAM process. In this sense, the holistic approach suggested by Plocher et al. [Plocher 2016] could be implemented by the use of CAD platforms, their development, and their related-based approaches.

2.4 Process Design

While product design should address additive manufacturing capabilities for improved solutions, process design must transform the expected requirements into actual performance. In particular for Design for Additive Manufacturing, since there is a strong connection between design and manufacturing this phase is fundamental.

Figure 15: An industrialized build job for L-PBF process.

Product design aims to the effective achievement of enhanced products requirements related to the high geometrical complexity allowed by the technology. Process design, or rather Industrialization, aims to improve process reliability concerning not only feasibility and economic considerations but also to achieve the aforementioned requirements through the reduction of many potential manufacturing flaws. DfAM must therefore not be limited to the product, but it must be extended to the production system [Thompson 2016]. Each build job has to be identified as a design object with its own requirements and characteristics to be designed and improved [Alfaify 2020]. Thus, Wiberg et al. explain that the industrialization task, or rather the preparation of the manufacturing process, is, therefore, one of the main research categories [Wiberg 2019]

In fact, process design aims to obtain effective and reliable manufacturing processes. Processes can be made more repeatable and cheaper by improving manufacts quality and by getting build jobs right the first time. These points can be achieved with the development of proper approaches and tools, which, as mentioned before, still represent one of the most important barriers to wide additive manufacturing spread. Again, specific methods and proper Computer-aided technologies (CAX) involving process preparation and simulation can support this phase to achieve process optimization.

In chapter 1, discussing the most used metal AM technologies, we mentioned a few disadvantages of PBF and DED processes. For PBF, we cited parts size limits, slow deposition rates, cost of powders, and also possible issues, such as material defects formation and parts residual stress and distortions. Whereas for DED, we considered limitations in shapes design and CNC programming, and again issues related to possible material defects and, in particular for large parts, relevant residual stress and distortions. Metal AM defects can be deepened found in [Taheri 2017]

All these aspects can therefore compromise:

- manufacturing process feasibility
- components quality and cost
- in-usage parts functionality

2.4.1 Components residual stress and deformation

To give an example, we can consider the issue of components' residual stress and deformation. Metal AM processes involve high thermal gradients since they are based on material melting and subsequent solidification. Expansion and contractions and shrinkage due to melting and solidification processes of metals entail residual stress that induces shape deformation. Details about this phenomenon can be found in [Luo 2018] This issue impacts all the three aforementioned points.

Manufacturing process feasibility

Components' residual stress and deformation can lead to building process failure. A PBF process could stop due to excessive warping that leads to collisions between the parts and the roller of the recoating system to spread the powder. A DED process can be ineffective if high residual stress generated by fast material solidification involves large distortions. In some case, the material delivery can be impossible or in the worst case material stress lead to crack initiation. Moreover, even if a part can be built, distortions can make post-processing operations (e.g. hole drilling or surface milling) impossible, especially for optimized structures that present low material thickness.

Components quality and cost

Components' residual stress and deformation impact both parts' quality and cost. The lower is residual stress, the higher are mechanical properties of the material and expected components' structural performance. The lower is components warping, the lower is the need for specific operations to achieve requirements in terms of dimensional and geometrical tolerances. Obviously, if the process gains reliability and build jobs are printed right the first time, the printing cost is reduced. Moreover, if fewer operations are necessary to meet product requirements, also post-processing costs are reduced.

In-usage parts functionality

Components' residual stress and deformation can compromise the expected product requirements. Components warping can lead to the impossibility to fit components in assemblies. Even if assembly operations are feasible, issues related to systems functionality can occur due to working in off-design conditions. Moreover, if materials presents defects or if it is affected by residual stress, even if material properties are sufficient, the formation of crack initiation spots is. This, considering material fatigue life, can probably cause failure during working conditions considering components' lifecycle.

The process design phase has a huge impact both on product defects and process flows as those already mentioned, and DfAM workflow issues as well. In order to prepare an additive manufacturing process and address the three introduced points, we can describe the process design phase, or rather industrialization, of a metal AM process.

2.4.2 AM Industrialization and process issues

Industrialization is the required step to make parts manufacturing process reliable. Concerning AM, it is one of the most important elements between design and manufacturing [Vaneker 2020], and the main tasks that compose this phase are coarse modelling and build preparation. The former is to produce CAD crude models components that undergo additive construction and further post-processing operations. The latter is to set up the build job layout and machine programming for components production. Build preparation generally requires parts manipulation, orientation, positioning/nesting, and support generation. Afterward, also slicing definition, path generation, and process parameters selection are required [Wiberg 2019].

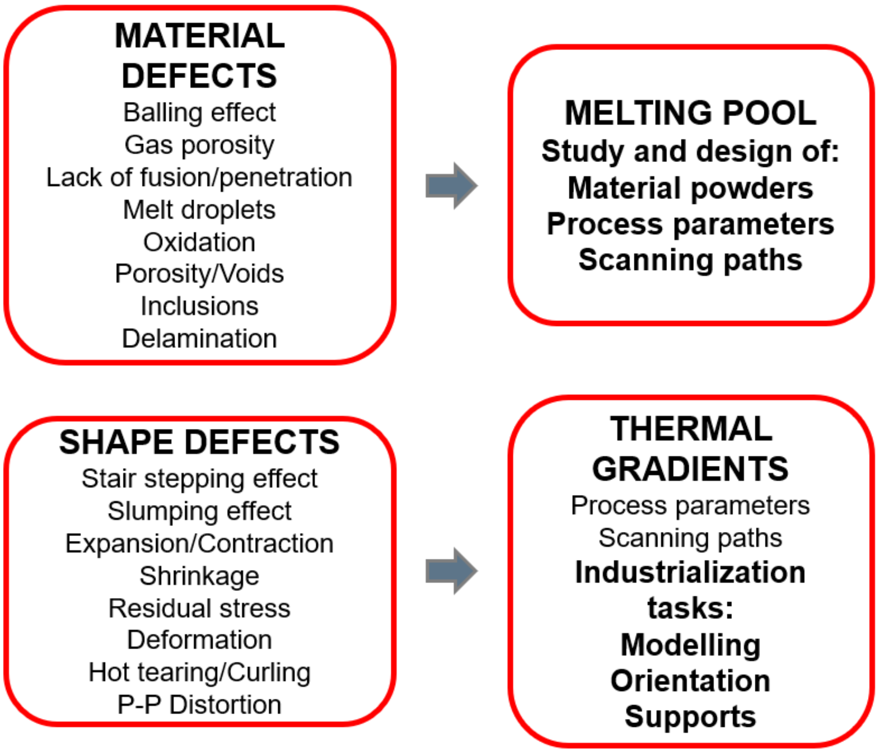


Figure 16: An overview of typical L-PBF defects and strategies to mitigate them

Industrialization operations have a huge impact both on products flaws and defects DfAM workflow issues. Tahari et al. explain that actual components application is thwarted due to the existing lack of process consistency and significant variation in physical properties between parts [Taheri 2017]. Zhang et al. collected a comprehensive review of metal AM defects and flaws [Zhang 2019]. Typical material-scale defects are bulk porosity, gas porosity, oxides and inclusions formation, microstructure alteration, lack of fusion, lack of penetration, or even material delamination. These flaws can worsen mechanical properties or represent sources of crack initiation that can lead to part failure. Whereas part-scale defects are stair-stepping effect, slumping effect, shrinkage, residual stress-induced deformations, hot tearing, and curling. Residual stress entails low mechanical properties, shape defects can affect subsequent post-processing, and they can compromise components functionality, assembly, and behavior. Recently, Mostafaei et al revised the PBF general microstructural defects (e.g. balling, lack of fusion, keyhole porosity, spattering, residual stress, cracking, delamination, etc.) considering the respective process stage (powders, process, post-process), considering their formation, mitigation, and prediction [Mostafei 2022]. Material-scale flaws are mainly influenced by process parameters selection (e.g. energy-related, scan-related, powder-related, temperature-related manufacturing settings), lots of studies are based on DOE approaches and variables optimization to maximize mechanical properties. Whereas part-scale flaws are mainly influenced by parts shape (geometry) and build layout, or rather product and process design. A recent review confirms that build preparation operations such as parts orientation and support structures design affect defects, as the former affects dimensional accuracy, surface finish, and material anisotropy, while the latter affects parts warping and distortion caused by residual stress [Mostafaei 2022] There are some interesting DfAM cases including industrialization: some recent re-designs provide build preparation studies [Rosso 2021]; other research reports the actual implementation of interesting best practices [Mantovani21]. Nevertheless, the literature lacks guidelines for effective industrialization.

For example, generally, industrialization choices (e.g. parts orientation, supports generation, etc.) are often related to designers' and users' experience.

If we consider a PBF process, some guidelines can be provided by the ISO 52911 [ISO 52911] series that introduce process typical problems such as:

"– Shrinkage, residual stress and deformation can occur due to local temperature differences.

– The surface quality of AM parts is typically influenced by the layer-wise build-up technique (stair-step effect). Postprocessing can be required, depending on the application.

– Consideration shall be given to deviations from form, dimensional and positional tolerances of parts. A machining allowance shall therefore be provided for postproduction finishing. Specified geometric tolerances can be achieved by precision post-processing.

– Anisotropic characteristics typically arise due to the layer-wise build-up and shall be taken into account during process planning.

– Not all materials available for conventional processes are currently suitable for PBF processes.

– Material properties can differ from expected values known from other technologies like forging and casting.

-Material properties can be influenced significantly due to process settings and control.

– Excessive use and/or over-reliance on support structures can lead to both high material waste and increased risk of build failure.

– Powder removal post processing is necessary"

The standard provides a few possible guidelines that could be considered during process design. Some examples of best practices for the main steps are reported. Considering the support structures, we can find examples of their use in the connection between the part and the build platform, in sloped surfaces, or in holes or internal features. Considering the orientation, we have examples for longitudinal geometries, critical geometries, or multiple parts instantiation. Moreover, we can consider the effect of parts orientation on the amounts of supports or supports removal operations. Finally, we can see a few examples of orientation to contain parts warping by avoiding wide slices area extension.

Anyway, actually few examples of generic guidelines do exist.

Thermal stresses, deformation, and shrinkage are three factors that determine build success and that can be controlled by software. For this purpose, process simulation can be introduced to support process design by predicting construction behavior. Thus, it can be introduced in the industrialization phase to create methods and workflows driven by simulation results instead of general guidelines and user experience.

2.4.3 Process Simulation for AM Industrialization

For the purpose of this thesis, we are going to deepen finite elements based process simulation techniques suitable in the DfAM context. They will be considered as the key step to achieve process optimization in industrialization phase of the methodology that will be proposed.

Process simulation can be introduced to support process design by performing studies for future guidelines, by speeding up process parameters optimization, by predicting construction results supporting process optimization [Luo 2018]. For example, generally, industrialization choices (e.g., parts orientation, supports generation, etc.) are related to designers' and users' experience. Process simulation can therefore be inserted into workflows for enhanced industrialization based on predictive techniques, to drive process design. Prediction of the process instantaneous spatiotemporal heat distribution that governs the formation of distortions, defects, microstructure evolved and mechanical properties, which are a function of industrialization core (as parts are printed) becomes fundamental [Taheri 2017, Francois 2017]. Potential manufacturing flaws can thus be calculated, and some modifications of strategy can be implemented to effectively compromise between production performance parameters and part material properties [Vaneker 2020]. Certainly, the use of such approaches must be based on actual accuracy, reliability, suitability, in particular for part scale computations and applications [Francois 2017]. Actually, process simulation can be performed at different scale levels and Models are needed at multiple length scales. Depending on the specific physical phenomenon that has to be captured, different simulation approaches do exist. Models at multiple length scales will enable the development of the dominant physics basis within macro-scale models for use in component performance simulations [Francois 2017]. Bayat et al. recently classified modelling strategies. At meso-scale we can find conduction-based simulations (e.g., thermal models, thermo-metallurgical models, thermo-mechanical models) and flow-based simulations (e.g., CFD including or not surface deformation, multi-physics CFD). Considering the macroscale that is needed at part-scale level, the main approaches are the thermo-mechanical method, the inherent strain method, and simplified thermo-mechanical models or modified inherent strain models.

2.4.3.1 Thermo-mechanical method

The thermomechanical simulation consists of an analysis of the transients of temperature-induced by thermal loads present on a part during the printing process, followed by a static structural analysis guided by the temperature range of the analysis thermal. Thermal and structural analyses are therefore weakly coupled. As a first step, a heat transfer analysis is performed on the part with specific boundary conditions and the application of a heat flow. Once the heat transfer analysis is completed, computed temperature profiles are used for the static stress analysis of the part in order to predict the displacements. It allows the exact specification in time and space of the conditions of the process, and it offers precise control over the fidelity of the solution. The results can be also accurate and complete, but they can be computationally expensive if the temporal and spatial resolution is increased. Therefore, sundry simplified models have been proposed to balance accuracy and computational cost. Bayat classified them as the agglomerated heat source (AG), multi-step (MS), flash heating (FH), and adaptive mesh refinement (AMR) [Bayat 2021]. Generally, they are based on the simplification of scales, on adaptive meshes, or on lumping either the exact scan paths or few layers. [G. U. 3DEXperience]

2.4.3.2 Inherent Strain method

Inherent Strain or Eigenstrain simulation is an engineering concept used to consider all possible sources of induced permanent deformation from the process. The Eigenstrain Analysis has been widely used to compute residual stresses related to welding operations. A simulation-based on the Eigenstrain of an additive manufacturing process consists of a single analysis of the static stress of a part in which an Eigenstrain field is applied predefined according to an activation sequence of the representative elements (usually layer by layer). This process results in a distribution of residual stress and a strain field that can lead to distortions. This method eliminates the need for detailed information about the machine. Calculation of the inherent strain strains can be classified into three methods: analytical, numerical, and empirical [Bayat 2021]. However, in most practical cases it requires additional efforts to calibrate the values of Eigenstrain by means of physical experimental tests on the process. The results of the Eigenstrain method are generally more approximate than those of the thermo-mechanical one. of the cs. Moreover, it can be unsuitable for complex geometries. Sundry models and modifications have been proposed to overcome issues and improve the accuracy of the method. [G. U. 3DEXperience].

2.4.3.3 Process simulation workflow

Firstly, model discretization in the three-dimensional space is required. A finite element model is created for parts, supports, and build plate. The voxel approach is the most suitable for processing a tessellation such as the STL representation. Specific types of volume and surface mesh elements can be also used if the discretization is based on a CAD model. Proper connections between the elements must be created, and proper physical constraints are applied. The material that is processed has to be deeply characterized by introducing temperature-dependent data for elasticity, expansion, conductivity, specific heat, latent heat, and possibly a plastic law (e.g. Johnson-Cook). The thermal and structural analyses have to be set. Process data about the slicing and scanning path must be retrieved to set the layer-by-layer mesh activation and the energy source movements. Also, heat input distribution parameters should be specified. Process temperatures (both for thermal and structural cases) of parts, supports, and the build plate, as well as cooling data (e.g. convection and radiation), have to be specified. Lastly, thermal and structural analyses require proper computation step settings, to perform model discretization in time. Finally, the computation can be launched. Moreover, additional steps related to post-processing operations can be added, to simulate for example cooling, heat treatments, parts removal, supports removal, etc. Of course, they require proper boundary conditions and finite elements based modeling approaches, but they can provide results more suitable for actual applications.

2.5 CAX: Computer Aided Technologies

For a few decades development of systems, subsystems, products and processes has been supported by computer-aided tools. As mentioned before, from the 90s, the evolution and spread of computer-based design and simulation laid the foundations for the creation of “digital twins", to enable concurrent engineering approaches and cut down the time to market. We can consider a general product development workflow, composed of design, prototyping, testing, industrialization, and manufacturing. In the classic process planning approach, the main tasks are performed in sequence. Conversely, concurrent engineering is based on the parallelization of tasks so that they can start with the least possible delay, which becomes possible just with the use of computer-aided design and simulation tools. Their use allows acquiring product knowledge in advance, benefitting from higher design flexibility, and overcoming the so-called “design paradox” (figure 17).

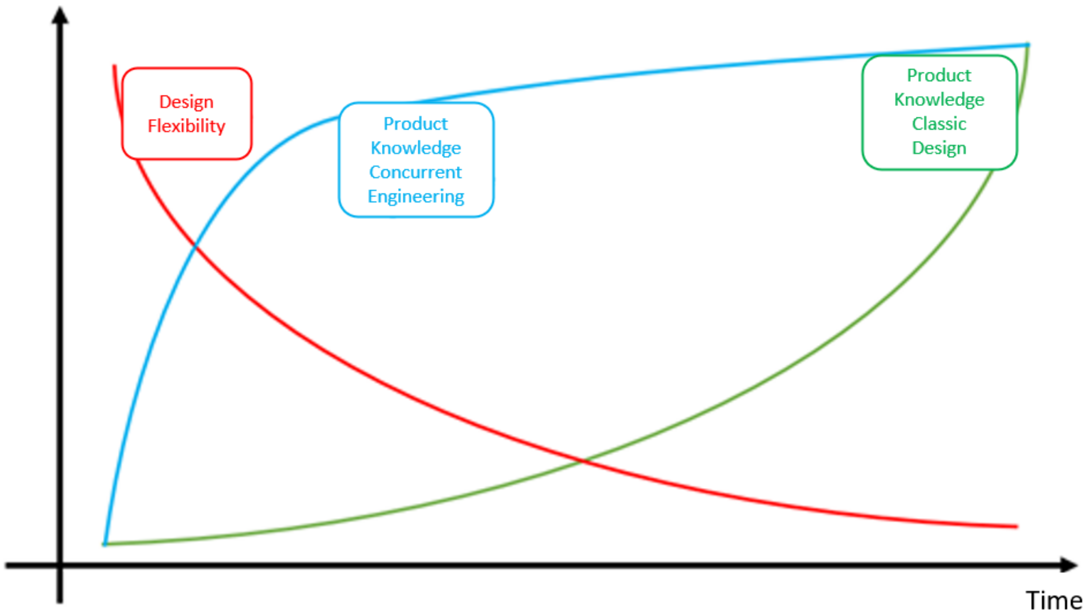


Figure 17: The use of CAX and CE to overcome the “design paradox”

Computer-aided design (CAD) is the use of computers (or workstations) to aid in the creation, modification, analysis, or optimization of a design [Narayan 2008]. This software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and create a database for manufacturing [Narayan 2008]

Among the additional computer-based technologies to support product development, we can cite the main categories of Computer-Aided Engineering (CAE), Computer-Aided Manufacturing (CAM), Digital mock-up, Virtual Reality and Augmented Reality, digital factory, and virtual commissioning. To give an example considering CAE technologies, can enable the simulation of products and processes including the physics behavior of solids and fluids, assemblies, kinematics, and dynamics. Moreover, they allow performing functional analyses, human factors analyses, aesthetic analyses, or even financial and market analyses. The use of these tools in concurrent engineering approaches required also to move from product/process management supports such as Product Data Management to Product Lifecycle Management. The PLM can be defined as a “concept that aims at integrating the various processes and phases involved during a typical product lifecycle with people participating in product development processes” [Sharma 2005]. Computer-aided technologies such as those mentioned allow shortening product development while improving quality and reducing product/process costs, thus meeting the DfX goals.

2.5.1 CAX for DfAM

Concerning AM, one of the main challenges for CAD tools is to address its potentials related to “design freedom”. Even if “complexity for free” is a key factor of AM, it is not always simple to integrate complexity in actual design approaches. Gibson describes different levels of complexity that should be supported by proper tools: shape complexity, hierarchical complexity, material complexity, and functional complexity [Gibson 2010]. The challenges are therefore represented not only by thousands of features but also by materials distributions or physical properties distributions, across size ranges of many orders of magnitude. To exploit complexity potentials in the design phase, many proposals to overcome those challenges are being studied, such as implicit modeling and multiscale modeling. Apart from geometry preparation by CAD, a prominent role in the DfAM workflow is played by CAM tools for process preparation. Moreover, CAE tools can be involved at different levels and with different purposes to support both the product design and the process design phases.

2.5.1.1 CAE

Milewski explains that “Engineering software tools developed to analyze and simulate heat flow, fluid flow, mechanical performance, or optimize the topology and shape of lightweight designs are being applied to AM designs”. As introduced before, since the analyses can space from mechanical, to thermal, to fluid dynamic effects, CAE tools can be used to simulate either the product or the process. For example, they can be used to perform topology optimization in the design phase as well as to run a process simulation in the industrialization phase. In this way, simulations can drive product design optimization, but also process design could benefit from simulation, prediction, and optimization. Generally, these tools are based on Finite Element Method (FEM), which is a numerical method to solve partial differential equations. Generally, the tools based on FEM application are called Finite Elements Analyses (FEA). For fluids computing, an analog method called Finite Volume Method (FVM) is used and the applications are called Computational Fluid Dynamics (CFD). To set a problem, the domain is discretized in the space dimensions by finite elements (mesh), which has a finite number of points. The differential equations are related to models of physics phenomenons, while the finite elements present associated material physical properties. A boundary value problem, therefore, results in a system of algebraic equations or ordinary differential equations to model the entire domain. Finally, various direct or iterative solution algorithms are used to solve the numerical problem and the results are computed for each point of the domain.

2.5.1.2 CAM

Computer-aided manufacturing (CAM) is the process of taking a CAD file, using the part definition to create instructions for a CNC (Computerized Numerical Control) machine tool, to perform the motion and machine control instructions to produce a component [Milewski 2017]. The tools are used for various manufacturing systems, to create the numeric codes that govern the processes. For AM they are fundamental tools since the layer-by-layer construction of objects is performed by machines that require specific numeric codes. In fact, as stated in previous chapters, in the build preparation step, once the layout of the build job and the process parameters are specified, the machine code is generated. Generally, we speak about “slicing” to refer to the process of slicing the geometry of the objects, creating the bidimensional layers that are sequentially built by AM to return the final tridimensional shape. Afterward, the scanning path to creating each layer is computed, and, finally, a code containing the initial and final operations and the instructions to create in sequence all the layers are generated. To perform these steps, specific CAM tools for AM are required. AM machines operate like a standard CNC machine (in particular for DED processes) but instead of removing material such as in turning or milling machines, they add material. Generally, CAM files are based on “M” lines to set machine controls, and “G” lines to set motion controls (“go” codes). The scanning path related to each bidimensional layer is controlled by G codes. They are used to control the position of the energy source within X-Y planes. Other functions, such as setting the temperatures, setting the speeds, setting the flows, or turning on and off the energy sources, are controlled by M codes. Therefore, the numeric code is composed of M and G codes specific for the machines that are generated within a build processor for AM. During the AM process, the machine controller will sequentially execute all the lines of commands until the process is completed.

2.5.1.3 The STL file

With respect to the use of CAX tools for the DfAM workflow, the main issues are related to the file exchange and data management due to the use of much specific software to perform the required tasks. As explained, sundry CAD-based tools help users in part design, CAE ones in topology optimization, product and process simulation and validation, and CAM ones in part industrialization. Typically, an STL file is used for data management as an interchange file between different software.

In particular, it has 3 main applications:

- It is used in design operations with CAD software, as a support for modelling parts starting from results of CAE topology optimization. The cloud of point defined by a density-based cut of finite elements based on selected iso-values are generally used to perform a tessellation that is exported as STL. The required redesign is therefore performed by overlapping the free-shape design and the tessellated representation.
- It is used for industrialization tasks in CAM build printing preparation software, for the exchange of the geometry of parts to be produced. In this environment it can undergo manipulations such as multiplying, scaling, sectioning, orienting, adding features such as support structures.
- It is used for additive manufacturing process simulation with CAE software, as input file to import a build job in the simulation software. It is generally the input for generation of voxel meshes for modeling parts, supports and the build plate.

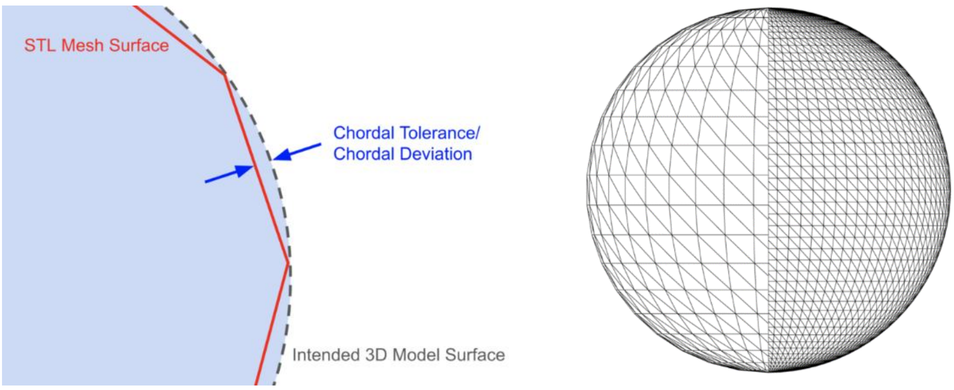


Figure 18: The STL file and the deviation from a mathematic

The STL file is a surface mesh that approximates a mathematical geometry representation. Its name is the abbreviation of STereoLithography, the first additive manufacturing process developed by 3D System in the early ‘80s. The mesh is formed by triangular elements, where each element is defined by the position in space of the three vertexes and a normal vector. The data can be stored either in binary representation or in ASCII format to be more easily readable or editable. Since it is an approximation, first of all, the STL file has deviations from the ideal mathematics, moreover, it can present many errors, such as unit changing, problems in vertex and edges connection, intersecting or overlapping triangles, degenerated facets, or bad aspect ratio triangles, bad edges, holes. The adoption of this format can lead to issues in file generation, fixing and editing in the CAD environment. Manual repairing is a highly time-consuming operation; automatic fixing tools are now very common but sometimes they are not completely effective, or they can lead to geometry problems. Despite STL models cannot benefit from CAD manipulation and parametric edition, anyhow they are in most cases necessary as design support for part development and re-design. Evidence of the above-mentioned issues emerges from case studies in the design and manufacturing of topology optimized components that make use of the DfAM workflow.

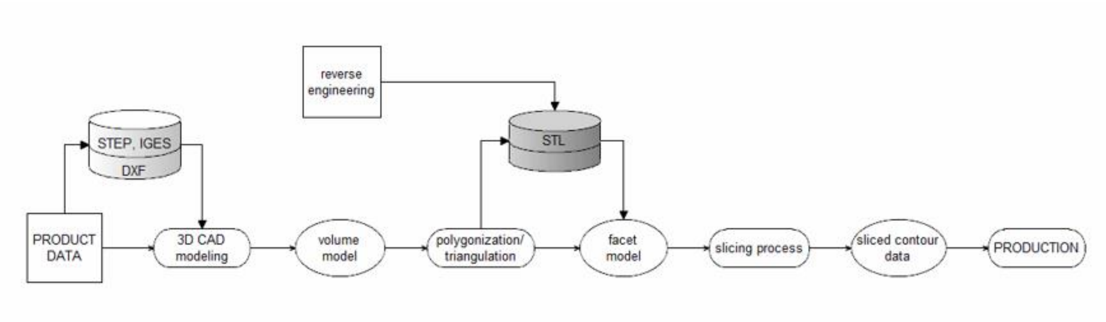


Figure 19: Adapted from ISO 17296-4

The additive manufacturing ISO standard 17296-4 [ISO 17296-4] explains that “STL file format (…) has established itself as a quasi-industry standard format for transferring data to additive manufacturing technology” ([ISO 17296-4], subsection 4.2.2), but it also states that “the STL data format is unsuitable for exchanging data between CAD/CAM systems because the geometry is irreversibly faceted” ([ISO 17296-4], subsection 4.3.1). In addition, it warnings users that the representation must be faultless and that there could be troubles in data management based on STL files.

There are considerations about guidelines to follow for triangulations and it even asserts that “data set repairs can be very time consuming and costly and therefore require individual approval” ([ISO 17296-4], subsection 4.3.1). In fact, according to the standard, the STL file has to be used only to send the geometry information for the slicing operation and additive fabrication process. Figure 2 depicts the scope of STL as reported in the ISO standard.

3 Computer Based Methodology

3.1 The DfAM workflow

Considering the methodology and tools state of the art described in previous chapter, to define the objectives of this work, hereafter the research gap is going to be introduced. This is provided from the perspective of research and industry, since both actually drive the developments of metal AM. Referring to the analyzed DfAM approaches and CAX tools, we can provide a synthesis of the DfAM workflow generally implemented to drive product and process optimization.

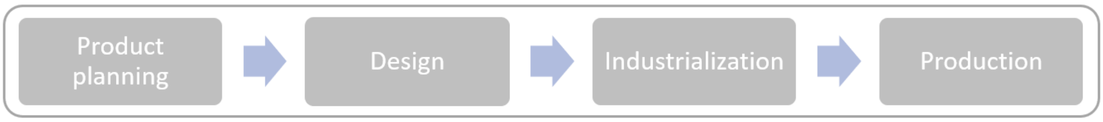


Figure 1: The general DfAM workflow

The basis of DfAM workflow is an iterative refinement of the starting model of the part with respect to Design and Industrialization constraints to respectively improve the part shape and the associated printing process. The input is the Product Data, which is made of the information (models, product analyses, assembly analyses, objectives, constraints) that is required for the design. The output is the Production, or rather the 3D printing process and the other related operations (e.g. post-processing, CNC machining, and testing). The whole approach relies on specific tasks listed as follows.

Product Design (*Design*)

- Model Preparation
- Topology Optimization
- Design Interpretation
- Product Simulation

Process Design (*Industrialization*)

- Coarse Modelling
- Build Preparation
- Process Simulation

3.1.1 Product design workflow

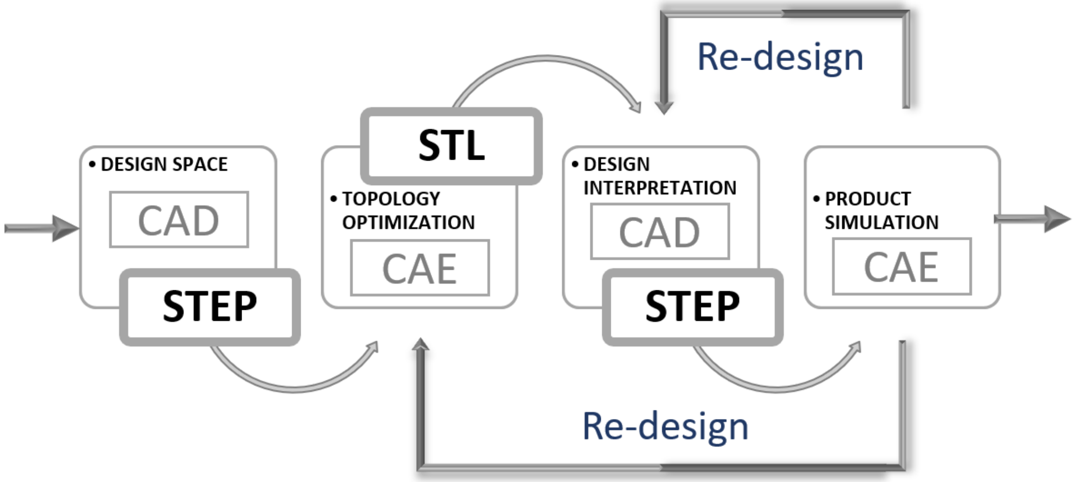


Figure 2: A general Product design workflow

The Product Design and the Process Design phases, which constitute the two main elements, aim to perform product optimization and process optimization. With respect to the Design phase, Model Preparation is the first step that returns the boundary conditions for subsequent optimization. Definition of design space (DS), or rather the model containing the permissible and forbidden volumes for shape computation, is required. In order to do that, a mathematical representation (generally the original part) can be imported as support, otherwise, it can be directly modelled through CAD software. An assembly analysis is required to define the maximum volume for the design space, according to the operative and assembly constraints. Generally, a non-design space (NDS) is also required, so that volumes that must be kept for functional regions are defined. A neutral representation file of these geometries is the input for Topology Optimization. A Finite Element -based CAE software computes the optimized shape of the part. The result is usually a cloud of points that could be manipulated to export a tessellated representation. In most cases, the STL file is used as support for the Design Interpretation, or rather the geometry reconstruction to be performed in a CAD environment, which is recognized as a highly time-consuming operation. A neutral representation file is generated from the model of the optimized part and is then imported into a Finite Element Analysis CAE software in order to perform the last step of the Product Design phase. Product Simulation evaluates the expected performance of the part. The results of the analysis (e.g. structural, or also thermal, kinematic, dynamic, etc.) are used to improve part features working on its geometry. At this point, some iterations in the workflow between just Model Preparation and Product Simulation or even Topology optimization, Model Preparation, and Product Simulation are necessary so that part optimization can meet the design requirements. If some design constraints change, all the Product Design workflow must be repeated.

Take home message:

One of the major challenges for product design is to efficiently achieve "ready to print" models.

3.1.2 Process design workflow

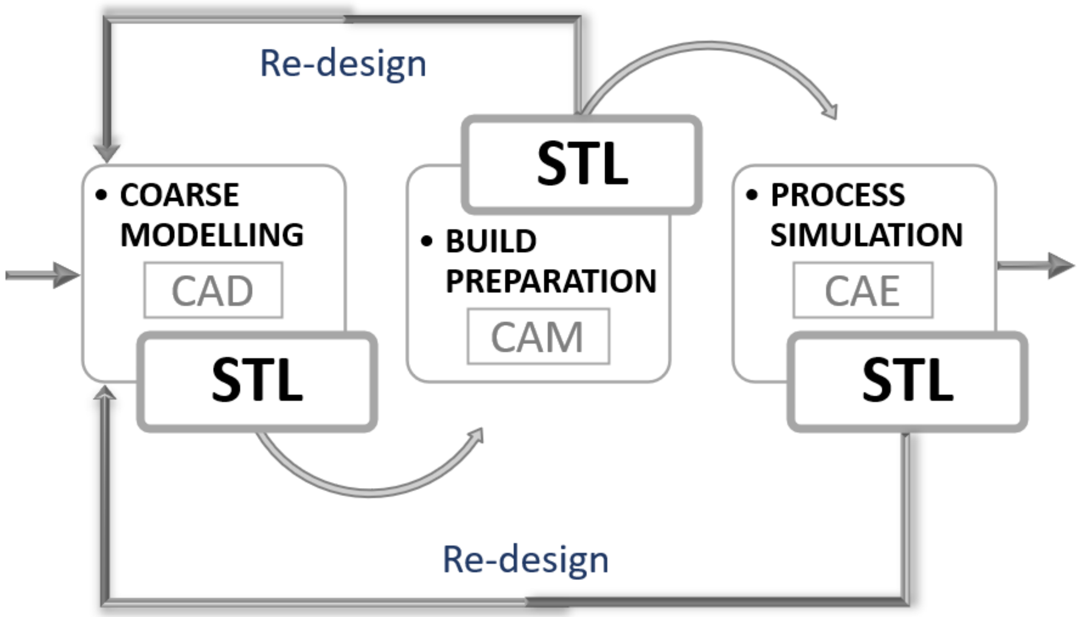


Figure 3: A general Process design workflow

Once the product optimization is achieved and the final design is ready, the Industrialization phase can start. Technical product data (e.g. drawings and specifications) can be also produced considering the manufacturing process and the expected post-processing. Coarse Modelling is the first step of Industrialization that creates the crude part models through CAD software. Usually, a tessellated representation of the geometry is then generated and an STL file is imported in a specific CAM software for AM to trig the Build Preparation. Generally, the part requires some modification considering the building strategy and so some iterations between

CAD and Build Preparation tasks occur. The output of this step is the build job to be printed. In order to optimize the industrialization, a tessellated representation of the build job is created and an STL file imported into a Finite Element -based CAE software so that Process Simulation can be performed (e.g. thermomechanical simulation). The results of the analysis are used to modify either the geometry of the parts by CAD or the Build Preparation tasks, so some iterations are required in order to meet functional and technological targets. Again, if some Industrialization constraints change, all the Process design workflow must be repeated. After the process optimization is achieved, the build job is ready, the NC code for the machine can be generated (generally through a build-processor software) and the Production can start.

Take home message:

One of the major challenges for process design is to achieve the result of "print right first time"

3.2 Research gap

We can observe that, even though the use of additive technologies firmly joins a CAD mathematical model and the physically printed component, the workflow from the design concept to the definitive build job results in many sequential steps which may have complex and slow relationships. For example, data consistency is compromised by many file exchanges. Very often, required operations are not reversible and, consequently, re-design loops necessary to achieve product and process optimization become difficult and entail increased product development lead time and costs. This happens each time geometries are converted to tessellations such as the STL file. Moreover, it is difficult to select the redesign loops that are required to achieve effective optimizations, as many redesigns may be required to achieve the design and manufacturing targets.

- Considering product design, main gaps are to ease and speed up workflows. Design exploration should be promoted as well as systems to select between variants should be developed. Redesign and design interpretation should be minimized; indeed, automation can be introduced and integration of optimization techniques can be enabled.

- Considering process design, main gaps are the need of effective guidelines and the improvement of simulation suitability. Process simulation can be introduced in the industrialization phase to create proper methods sustained by computation instead of general guidelines and users experience.

- Tools are required to implement design approaches [Wiberg 2019 ,Reddy 2016]. Tools and methodologies should evolve together by introducing proper features and by supporting the designer's intent [Alfaify 2020]. In fact, approaches are strictly related to the capabilities of CAX tools. Current design tools still show room for the development to satisfy the needs of Design for Additive Manufacturing.

- Referring to the DfAM research, studies still confirm that knowledge is the barrier that holds back further adoption of AM in industry [Vaneker 2020]. The development of knowledge, but also tools, rules, guidelines, workflows, and methodologies in general is one of the technical principal challenges of AM [Thompson 2016]. Moreover, the needs of holistic approaches and integration of product and process design are suggested [Plocher 2016, Wiberg 2019].

- Considering the AM research landscape [Schmidtt 2021], we can observe the amount of vertical research related to specific aspects of machines, materials, and processes. On the side of the process chain, there is need of integration and automation. The improvement of data consistency would regard therefore not only the tools but also the process chain itself. The improvement of horizontal research considering design approaches and related workflows is therefore fundamental to spread the use of AM for practical applications.

Finally, by synthesizing these points, the focus is on the methodology, to improve the process chain by providing systematic approaches that promote integration and automation. The research project is focused on the development and application of integrated DfAM methodologies to perform product and process optimization. For this purpose, a Simulation Driven Integrated Approach is proposed.

3.3 Simulation driven integrated approach

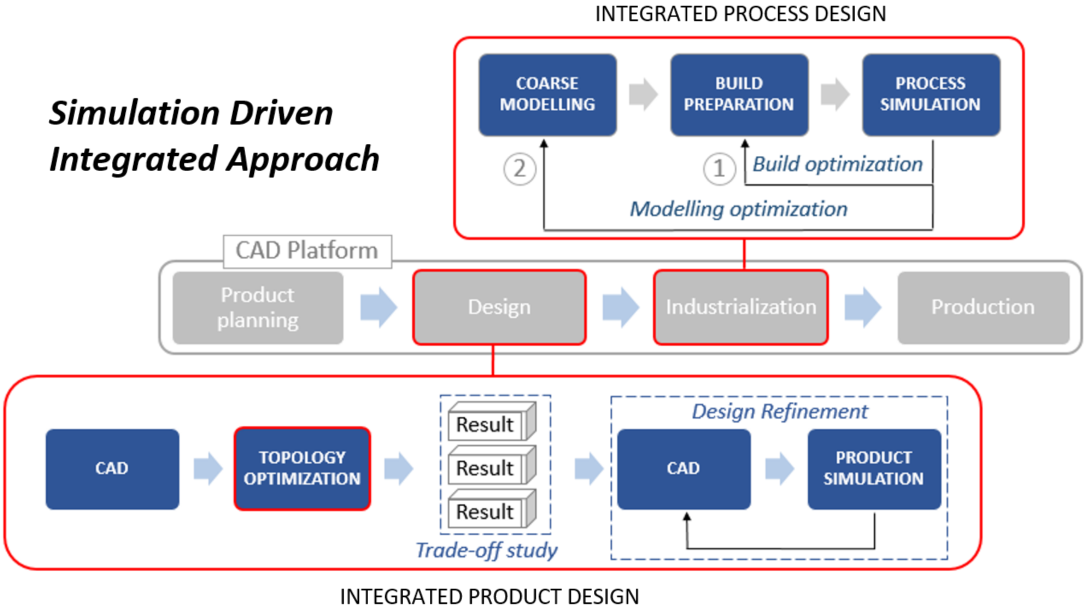


Figure 4: The Simulation Driven Integrated Approach

The Simulation driven integrated approach is depicted in figure 4. Chapter 4 will deepen the of each phase, providing proper studies to demonstrate its effectiveness and to prove its suitability. Therefore, the key points for its development about the tools, the product design, and the process design, are now synthesized.

3.3.1 CAD Platforms

The first point concerns the analysis of critical issues in the DfAM workflow. In most cases, sundry specific stand-alone software is used to perform the different tasks that form the described general workflow. This can lead to issues in the digital process chain at the global level, related to data management and exchange. In order to overcome this issue, the introduction of CAD platforms as backbone tools to shorten product development time and raise its efficiency has been proposed. Moreover, the potentials offered by the integrated platform should be evaluated. Therefore, the first validation of CAD platforms at the global level (related to the digital process chain) becomes necessary, considering all the design and industrialization tasks. In order to do that, the re-design of an automotive component (Steering knuckle) to be produced by Powder Bed Fusion (PBF) process is performed (Chapter 4.1.2). Subsequently, a local level evaluation (related to the specific operations) is required to test the effectiveness of the singular step-oriented tools as well. In order to do that, the second validation of CAD platforms becomes necessary, considering all the design and industrialization tasks, and the and the entire workflow for the development of an optimized automotive component (Steering knuckle) is considered for this purpose (Chapter 4.1.3). Finally, integrated DfAM methodologies based on CAD platforms can be defined.

Tools

The tools involved in the development of the holistic design approach are CAD platforms. The considered tools are commercial software so that it is both available on the market and accessible by users and companies for DfAM implementation. The CAX tools' capabilities and their benchmark has been defined as fundamental [Reddy 2016, Saadlaoui 2017]. The benchmarked tools are Dassault Systèmes 3DExperience [3DEXPERIENCE], Siemens NX [NX], Autodesk Fusion [Fusion 360], and PTC Creo [Creo: Design]. They are configurable CAD platforms to support the design process by combining modelling, simulation, and data management through the possible integration of CAD, CAE, CAM, and PLM tools. Actually, all of them represent software from the state-of-art for product and process design, suitable for DfAM implementation. The tools list is quite comprehensive, but a remark is that additional software can be considered, as well as such tools are continuously evolving to support designers' aims, as previously discussed in chapter 2. The assessment framework involved to sustain the tools selection phase is described in Appendix.

3.3.2 Product design

The general framework composed of the main tasks of DfAM was introduced and discussed. The scenario of lightweight and functional structure design, the role of topology optimization for this purpose, its current state of the art, and the forthcoming advances were described. Starting from the definition of an integrated approach based on CAD platforms, the following key factors need to be studied:

- different design solutions exploration
- product process-related design constraints implementation
- number of required redesign loops
- suitability and effectiveness of the approach

- product development lead time

Therefore, a few design workflows will be discussed, considering integration and automation decision-making points, pros and cons, possible variants, and research hints. Systematic approaches for TO and DfAM integration are proposed, and they are validated through the re-design of an automotive case study (Brake caliper) to be produced by PBF process (Chapter 4.2.2). Integrated simulation-driven design studies demonstrate the methods' suitability to industrial context for the redesign of components to be produced by metal AM.

3.3.3 Process design

The key aspects of industrialization, related issues as well as reference to techniques to reduce or prevent these effects were provided. A design method to perform metal AM integrated process optimization is therefore proposed. The aim becomes to minimize process-induced defects and flaws of AM-based manufacturing of metal products, such as residual stress and distortions. The approach consists of industrialization task improvement based on modelling optimization and build optimization sub-phases supported by numerical process simulation. A Selective Laser Melting (SLM) finite-element based thermo-mechanical simulation is setup to model both the build process and the post-processing operations (e.g. thermal treatments, buildplate removal, supports removal). A first case study (Steering upright) demonstrates the simulation implementation feasibility through a CAD platform (Chapter 4.3.2). The second case study (Cantilever beam specimen) validates the simulation results compared to experimental data for further method application (Chapter 4.3.2). The design method is finally applied to perform the industrialization of a part-scale level automotive case study (Brake caliper) (4.3.3). Process simulation-driven studies demonstrate the method's suitability to industrial context to improve industrialization in the redesign of components to be produced by metal AM.

4 Development and application

4.1 Assessment of CAD-platform-based approaches

The first point of the approach is related to the use of CAD platforms. Therefore, CAD platforms are introduced as backbone tools to shorten product development time and raise its efficiency. Nevertheless, such type of tools must be evaluated with respect to the tools available at the state of art in general DfAM workflows. Moreover, eventual potentials integrated platform should be evaluated. In order to do that, considering the general DfAM workflow, we can distinguish two different assessment approaches:

- CAD platforms validation of at global level (related to the digital process chain)
- CAD platforms validation at local level (related to the required specific tasks)

The CAD platform selected for the local level evaluation is the Dassault Systèmes 3DExperience. The product-process design platform fundamentally integrates the design environment of Catia suite, with CAX engineering tools of Simulia and Delmia and PLM management of Enovia.

4.1.1 Case study for the Assessment of CAD-platform-based approaches

A Formula SAE wheel knuckle is identified as a case study to assess the introduction of the 3DExperience CAD platform as a support tool for the DfAM workflow. This component is a key part for vehicle dynamics performance in racing cars, since non suspended masses have to be minimized in order to guarantee cornering performance, due to the better tarmac-tyre contact. Dumbre et al. [Dumbre 2014] analyzed wheel knuckle behavior in critical working conditions and defined a modeling approach for simulations. Sundry examples of design optimization of this component have been explored. Generally, this was done embracing traditional technologies and, for example, Bhardwaj et al. worked on the design optimization for a part to be produced by CNC milling [Bhardwaj 2018], while Harzheim et al. achieved the optimization for a part to be produced by casting [Harzheim 2006]. Conversely, few examples of DfAM including Topology Optimization of a wheel knuckle to be produced by PBF AM process exist, such as the Electron Beam Melting manufactured one from Walton et al. [Walton 2017]. Lately, other cases can be found in [Jankovics 2019, Kim 2020]

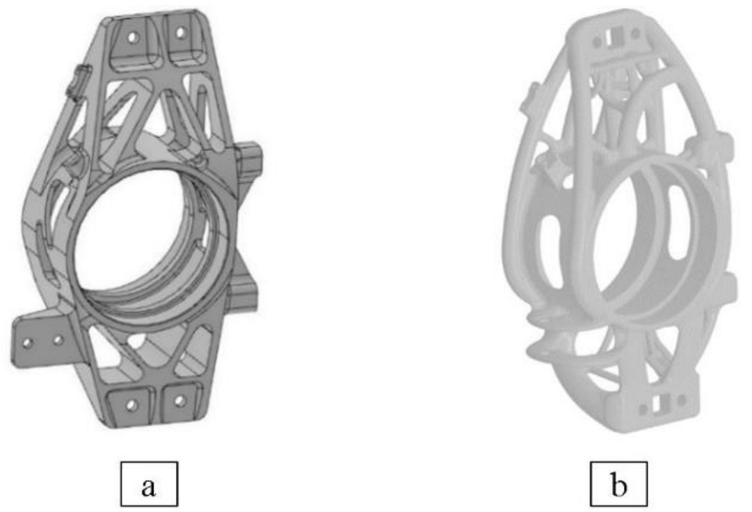


Figure 1: Original component model (a) and first topology optimized model (b).

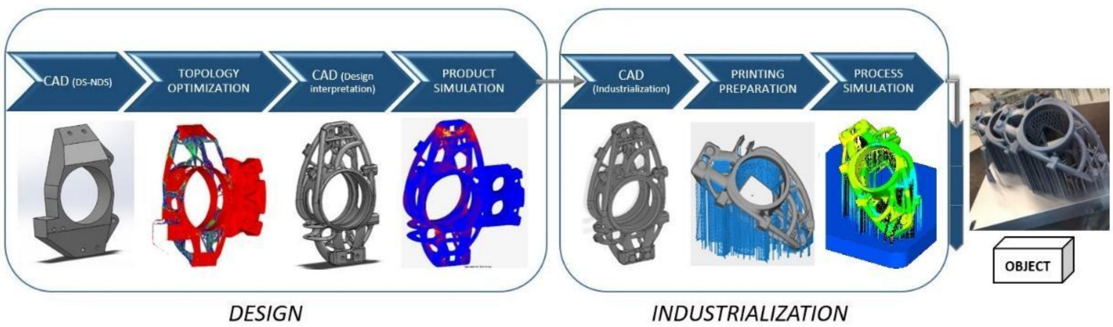


Figure 2: DfAM of the benchmarked part

The case study component, originally made by traditional subtractive technology, had been re-designed requiring the use of many specific software for the different tasks, and then printed by Selective Laser Melting (SLM) PBF process with benefit of weight reduction. The original CNC milled part was made by 7075 Ergal, presenting 2.81 kg/cm$^{3\ density}$, 72 Gpa elastic modulus, about 500 Mpa yeld stress. The component therefore weight 436g, but had stress concentration of about 300 Mpa. The design objective was a mass reduction of 10%, with constraints related to part stiffness, reduction of stress concentrations, part couplings and kinematic fitting in the wheel-suspension assembly. According to the general workflow described in chapter 3, the steps and the tools involved for the benchmarked part operations are depicted in Fig. 2. In particular, Dassault Systèmes Solidworks had been used for CAD modelling and re-design operations, Altair Optistruct for Topology Optimization, MSC Marc for Product Simulation, Materialise Magics for Build Preparation, PTC Creo for CAD coarse modelling and industrialization (crude model, solid supports), MSC Simufact Additive for Process Simulation.

4.1.2 Global level validation

The founding idea is to improve the state-of-the-art workflow. This could be done by removing the need to use the STL file and to exploit product-process platforms which integrate CAD, CAE and CAM applications to enable product and process design, as well as product and process simulation. Data exchange and data conversion to different file formats to be imported in the different tasks may be not required. Nowadays CAD platforms include a plethora of applications integrated in a common environment which allow an unambiguous data management throughout the product lifecycle. Consequently, it could be possible to define just one main CAD model to work on, from part concept to production. The different applications that integrated in the CAD-based environment are then switched to enable the execution of the different tasks. In this way it becomes possible to keep parametric and associative properties, which are intrinsic in the CAD model. The main CAD model can be introduced in product assemblies or product physical simulations, as well as in process preparation assemblies or process simulations. Each redesign can therefore be performed on the main CAD model at different levels of the product lifecycle. Consequently, the design intent in feature definition to keep intelligence in the model for the required operations in both product and process development becomes fundamental.

Finally the final data could eventually be exported in STL, but also in other formats suitable for additive manufacturing such as AMF (standardized Additive Manufacturing File), 3MF (XML-based data), MTT (metadata) files for direct production, or also CLI (Common Layer Interface) and SLC (SLiCe) which are basically representations of the slicing.

Case Study - Topology optimized steering upright ADM

A first topology optimized steering upright had been designed, following the state of the art DfAM workflow, see Fig. 2.

The case study is now re-designed for additive manufacturing to validate design and industrialization in the Dassault Systèmes 3DExperience CAD platform. The design objective remains weight reduction, since the vehicle non suspended masses must be minimized. The re-design for additive manufacturing of the component benefits of the limitations of technological constraints just for functional features and parts integration for assembly consolidation. In order to define the design space, some technical improvements have been introduced in the model, such as radial supports for brake caliper, double bearing housings instead of one, exciter slot, integrated steering rod connection.

An assembly analysis has been performed, to guarantee couplings with upper and lower wishbone brackets and elements of steering and braking systems, with the feasibility of assembling operations (space for fasteners, tools and movements) and room for the envelope of the steering rod and the wishbone to be considered. The design space has been partitioned and functional surfaces and non-design space volumes have been detected. 3(a)-3(b) respectively depict the configuration of the original wheel knuckle with respect to mounting assembly (a), and the related design space (b).

In order to perform topology optimization, a finite elements model is set up by meshing the design space and defining loads and restraints for the simulation. Three load cases have been introduced, to simulate car bump or rather vertical jump, cornering at maximum speed, braking at maximum deceleration. Vertical, longitudinal and lateral forces are applied at the wheel center point, whereas braking forces are applied at the brake caliper pads contact surfaces. The topology optimization has been set at the same time with the three load cases, with the target mass reduction constraint and the objective of maximizing part stiffness. Product analysis and simulation are then the subsequent step.

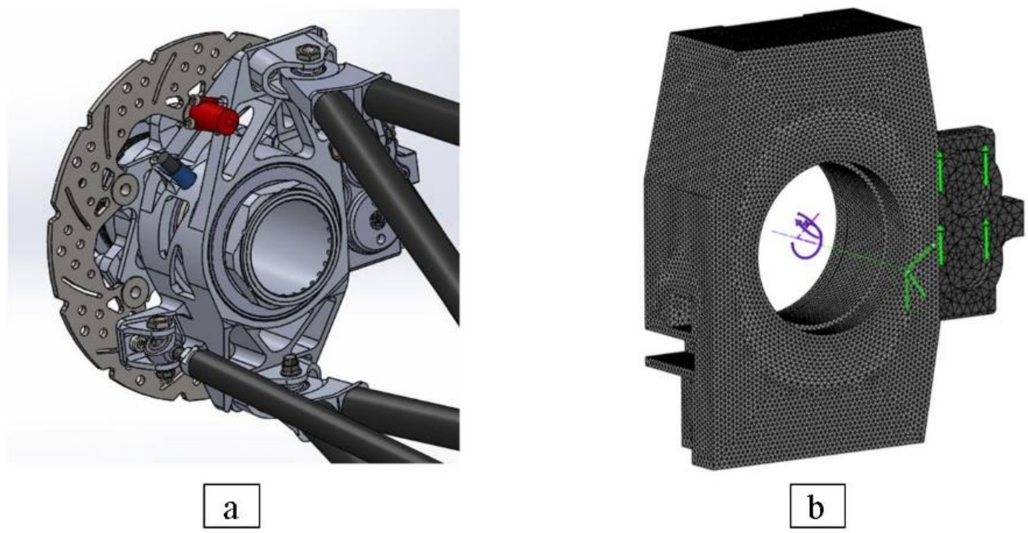


Figure 3: Assembly analysis for design space definition (a) and finite elements model with mesh and set-up of load cases (b).

Structural validation has been performed, to evaluate part stiffness and part stresses compared to the three load cases. In addition, digital mock-up (DMU) of the component inserted in the wheel-suspension group assembly has been performed with assembly operations and check for clash. Final model has been obtained with the introduction of functional features and surfaces so that the part could work properly in the assembly. To proceed toward the industrialization of the component, the right and the left wheel knuckle crude models are created, providing allowance on the surfaces to be machined and studs on spots to be drilled. A PBF machine environment for the SLM 280HL has been created, construction parameters have been set and the build plate has been inserted. Part orientation has been calculated with an optimization algorithm to both minimize supported areas of the parts and the support volume. Moreover, to bear considerable areas, firstly CAD designed solid supports have been created. Afterwards, vectorial line and volume supports, and cone supports are added to complete the task, checking the operation through the slicing analysis and completing the build job preparation introducing proper specimens.

Results

The re-designed part with the 3DExperience CAD platform is considered. The result of topology optimization based on all the three load cases is shown in 4(a). An automatic shape generation tool has been used to obtain a concept shape setting a 0.52 iso-value for density. At the end of this step a manipulable solid model has been created as output of the topology optimization (Fig. 4(b)-4(c)). The final part obtained with some design improvements and the introduction of missing functional features is shown in Fig. 4(c).

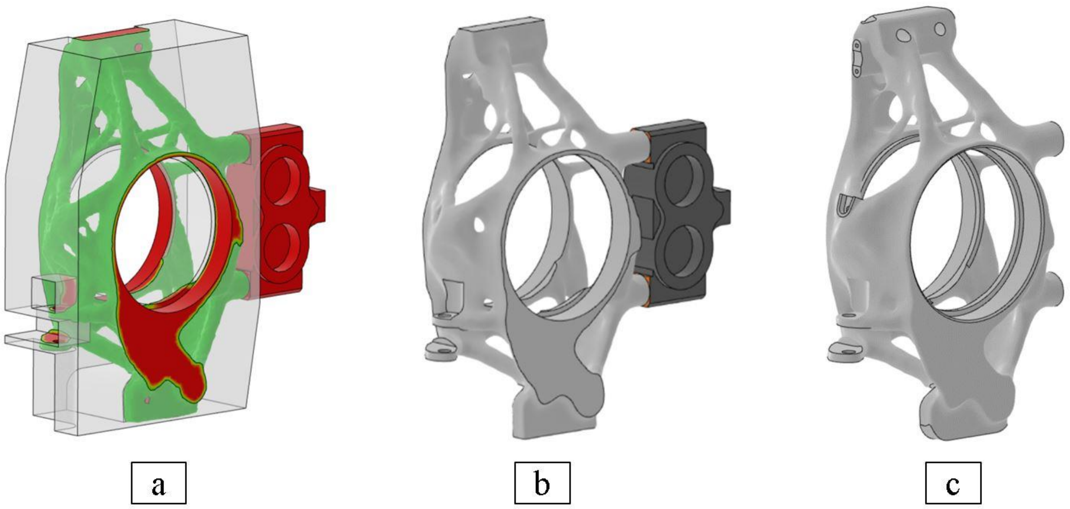


Figure 4: Topology optimization result (a), generated concept shape (b), final design model (c).

The concept has been analyzed by finite element simulations of the three load cases. Thanks to the branched natural shape and the absence of sharp edges, the results are therefore:

- main stresses are all below 200Mpa
- stiffness is comparable to the original component
- the weight of the new concept is about 382g

Figures 6(a)-6(b) show the stresses on the component with respect to the cornering load case and the digital mock-up of the concept part into the wheel and front suspension assembly.

The weight for the component rises to 389g. Figure 7 shows the industrialized part, with CAD designed solid supports, that lead to savings up to 40% of material, energy and build time for supports. Results of the topology optimized part, designed in the 3DExperience CAD platform can be analyzed and a comparison with the initial optimized component, that was designed following the general approach can be done.

Considering almost the same values of stiffness and stress concentration, that are far below the original the CNC-milled part, the weight of the parts can be compared, see Table 1.

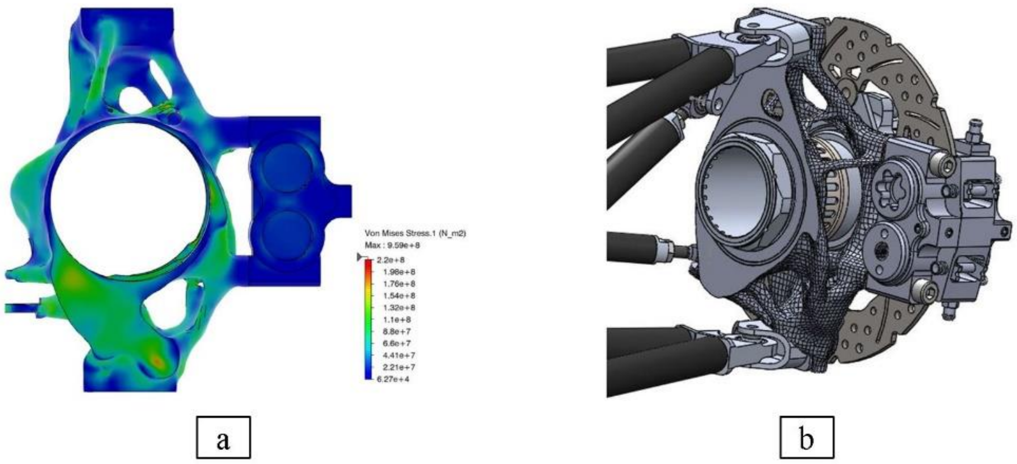


Figure 5: Concept model finite elements analysis (a) and digital mock up analysis (b).

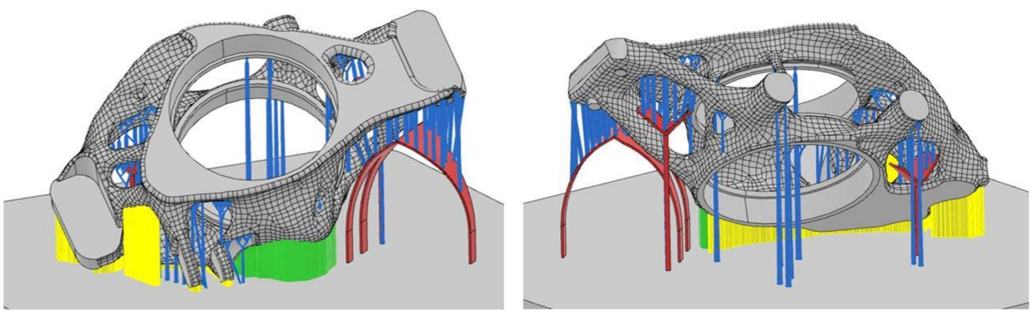


Figure 6: Industrialized job for the left raw part.

Table 1. Weight comparison between the components.

CNC-milled	AM (state of the art)	AM (CAD platform)
436g	401g	389g

Some considerations can be extracted from CAD platform based DfAM. Topology optimization has been calculated at the same time with respect to the three load cases. An easily manipulable solid model has been obtained as output of this step, instead of a cloud point to be exported as STL and to be used as a support for geometry reconstruction. Design, optimization and product validation tasks have been made in the same environment due to the integration with the CAE applications, on the same parametric model, without need of data interchange, also for re-design steps. This model could be also used for industrialization, due to the integration with the CAM environment, exploiting CAD parametricity and associativity for part re-design. In this way even CAD designed solid supports could be introduced directly in the virtual printing environment. Also, industrialization became feasible without the use of STL files meshes, without issues in file generation, manipulation or reparation.

Consequently, it is possible to design topology optimized components entirely in the CAD platform, by switching between specific applications and working on a single model. STL file is not necessary as interchange element, as modeling support, for re-design, for printing preparation. Therefore, the use of integrated product-process CAD platforms can evidently improve the DfAM workflow simplifying operations and relations between tasks and can shorten product development workflow reducing time to product. The results will be discussed in Chapter 5

4.1.3 Local level validation

Local level steps for Design and Industrialization phases respectively are Topology Optimization and Product Simulation, Build Preparation, and Process Simulation. In both cases, re-design loops are required:

- to optimize the product with respect to the product objectives and constraints along the Product design phase;
- for process optimization acting on both part design and the build job preparation over the Industrialization phase.

The specific tasks to be performed in the four local levels, are related to the Product design and Process design workflows. In particular, starting from the general DfAM workflow discussed in chapter 3, we can consider details of the Topology Optimization workflow in the Design phase (chapter 2), and the process simulation workflow in the Industrialization phase (chapter 2). below.

The described tasks require express implementation in tools and since they affect the workflow at local level, Topology Optimization, Product Simulation, Build Preparation and Process Simulation must be tested. Therefore, the aim of this work is to implement the general method, understanding the behavior of the integrated tool at local level. The next chapter presents the CAD platform based approach that has been tested for Design and Industrialization phases with respect to the steering upright case study and the assessment approach for local level steps.

Case study, tools and assessment approach

According to the general workflow described in chapter 3, the case study is the topology optimized steering upright presented in chapter 4.1.1. While the DfAM required the use of sundry specific software to fulfil the required tasks (Dassault Systèmes Solidworks, Altair Optistruct, MSC Marc, Materialise Magics, PTC Creo , MSC Simufact Additive), the Dassault Systèmes 3DExperience CAD platform is now considered.

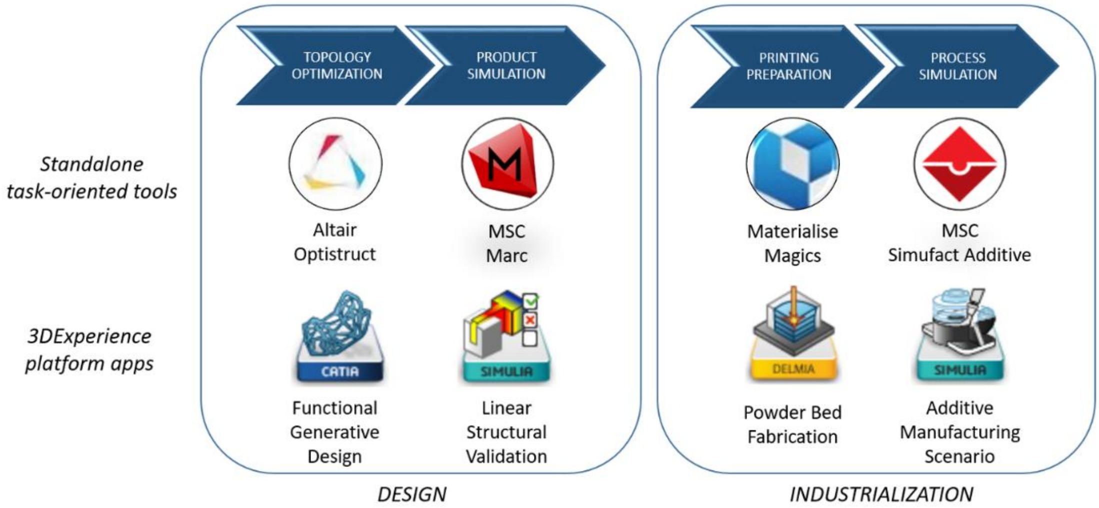


Figure 7: Standalone tools and platform apps involved in Design and Industrialization core tasks

For each of the core CAX based tasks of Design and Industrialization phases, the output of each standalone tool at the state of art has been identified as reference. This becomes the target for the operations performed in the CAD platform through the respectively use of specific apps, summarized in Fig. 7.

With respect to the first step, the output of Altair Optistruct is taken as reference. The 3DExperience application for this purpose is Catia Functional Generative Design, which integrates in a CAD environment Tosca solver to perform Topology Optimization and compute the shapes. The aim is to replicate the set up of three different loadcases and discover if the tools, starting from the same input data, will provide similar results despite of different features and computational algorithms. In details, bump is the first loadcase; it simulates the maximum load related to a vertical acceleration. The cornering loadcase is to simulate the load of a corner at high speed with the maximum lateral acceleration (tyre limit condition). Braking is the loadcase that simulates the load due to the maximum negative longitudinal acceleration. Table 2 summarizes the loadcases definition.

Table 2. Loadcases definition

Loadcase	Element	Value [unit]
BUMP	Acceleration	5.6 G [m/s^2]
	Vertical force	4400 [N]
CORNERING	Acceleration	2.5 G [m/s^2]
	Drift force	4215 [N]
	Vertical force	2810 [N]
	Drift moment	961 [Nm]
	Reaction moment	809 [Nm]
BRAKING	Acceleration	3 G [m/s^2]
	Longitudinal force	2700 [N]
	Vertical force	1805 [N]
	Braking force	885 [N]
	Transport moment	616 [Nm]

With respect to the second step, the output of MSC Mark is taken as reference. The wheel knuckle prototype had been validated through finite element (static and buckling) analysis simulations, in order to check, despite the mass saving, the adequate structural performance. In particular, the original CNC-machined part had some stress concentrations over 300 MPa. During part utilization and stress this behavior could lead to crack trigger on the material and eventually part failure. During the re-design operations, exploiting the branched organic shape, particular attention had been put to the limitation of part stress at 200MPa and the product simulation upheld that part behavior. The output results are the Von Mises stress distribution maps. The 3DExperience application for structural validation is Simulia's Linear Structural Validation, which involves Abaqus computation code.

The output of Materialise Magics is taken as reference for the third step. The job had been created introducing the part in the machine context, computing a precise orientation, designing special support structures and performing slicing analysis. The benchmarked job preparation had required part orientation to be optimized in order to minimize the need of supports, so that much less powder will be required (material, time and costs reduced) and the post processing step will be simplified. For support definition, both traditional vectorial support from Magics library and CAD-designed solid supports had been introduced. Solid supports provide material saving and let reduction of support anchoring on part surfaces. A total amount of 205 supports between block and cone type had been used both vertical ones and angled ones, with the aim of reducing part surface support anchor. The aim is to replicate the operations that brought the industrialized additive manufacturing job and verify if the Delmia's Powder Bed Fabrication application on 3DExperience, despite of different interfaces and features, could lead to a similar result.

Finally, the last step refers to the output of Simufact. Process simulation had been performed starting from the industrialized job made in Magics, exported as STL. Voxel mesh and connections had been created, thermo-mechanical AlSi10Mg material properties had been set, process parameters and temperatures had been created, thermal and structural analyses had been performed considering the phases from building to cooling. The simulation tool had been calibrated with process parameters of the SLM 280 HL machine used for part production and via experimental optimization. The aim is to run a preliminary process simulation, completing the operation to achieve the same type of result, which is in particular a displacement map and a deformed model. The 3DExperience application is Simulia's Additive Manufacturing Scenario. In this case the expected output should not be exactly comparable, since simulation will require then special additional tuning.

Results

Topology Optimization

A tetrahedron linear mesh with cell dimension of 2mm has been created in order to balance an accurate solution and computational cost. The structural model has been developed in order to replicate the physical behavior of the suspension mechanism. Figure 4 depicts the reference model of the component with the main geometrical features used to setup the optimization. Specifically, the holes for the fastening the brackets for uniballs of upper and lower wishbones, respectively #1 and #4; holes for the fastening the bracket for the coupling with the steering rod, #5; housing of the wheel bearings, #3; holes for the screws used to attach the brake caliper, #2.

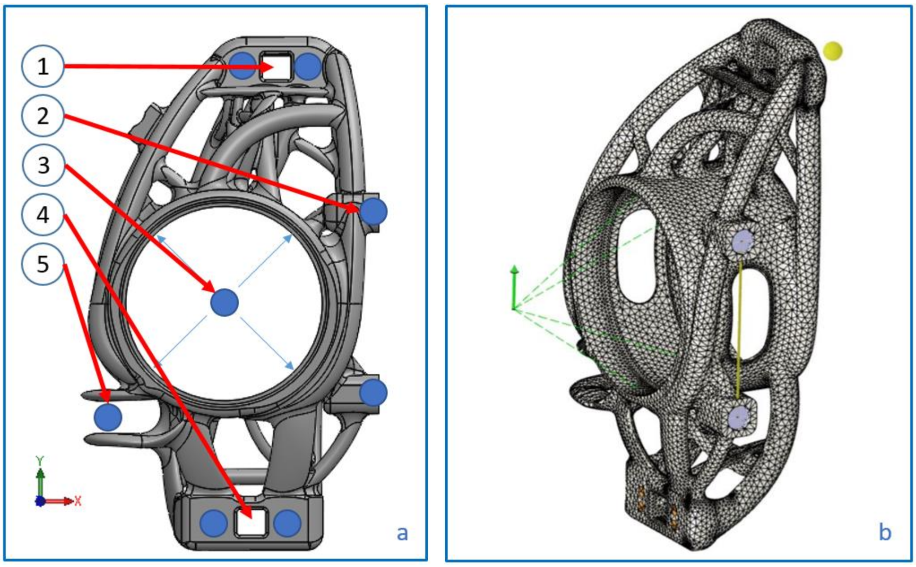


Figure 8: Component elements and finite element model

The benchmarked restraints setup was made of:

- RBE2 on the holes #1 with X Y and Z displacement on the control node at the center of the joint.
- RBE2 on the holes #4 with X and Z displacement on the control node at the center of the joint.
- RBE2 on the holes #5 with Z displacement on the control node coincident with the pivot axis.

In the Functional Generative Design application, the following setup has been created:

- Spherical joint on the axis of the holes #1 positioned on the center of the joint, with X, Y and Z displacement.
- Forbidden displacement on holes #4 with control node positioned between the two axis and X and Z displacement.
- Forbidden displacement on holes #5 with control node positioned between the two axis and Z displacement.

First and third cases return identical solutions, whereas the second case provides a comparable solution, except for the loss of a small lever arm.

The benchmarked loads setup was made of a RBE3 element connected with the surfaces of #3, with control node positioned at the wheel center. On this element all the loads (force and torque) related to the three different loadcases had been applied.

In the Functional Generative Design application, feature for remote load and remote torque have been used, connected with the surfaces of #3 applied on a point positioned at the wheel center, as depicted in Figure 4b.

The computation targets are the results from the bump, cornering and braking loadcases above described. With respect to the last two shape computations, the introduction of the brake caliper is required, since it contribute to the knuckle stiffness. A simulacrum is created and fit in assembly with the wheel knuckle, the meshes of both parts is created and they are connected introducing infinitely stiff elements on the holes #2. In addition, for the braking loadcase, forces acting on the braking pads are applied on the part. Topology Optimization is set with a stiffness maximization target (minimization of element compliance) and a target percentage mass value as constraint. Figure n.5 depicts respectively the results from Optistruct and 3DExperience, with respect to the Bump (Fig. 9a), Cornering (Fig. 9b) and Braking (Fig. 9c) loadcases.

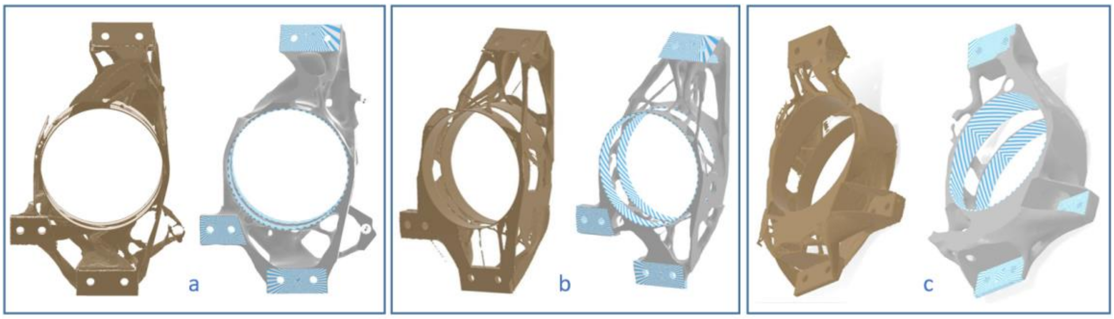


Figure 9: Topology optimization results

Product Simulation

The operations in 3DExperience can be performed on Functional Generative Design itself (if platform workflow is preserved) or anyway in Linear Structural Validation application. For the finite element analysis, a truss rod link between the holes for the fastening of the brake caliper has been introduced in order to replace the part taking into account its stiffness (Fig. 8b). The three loadcases (Bump, Cornering and Braking) have been simulated using the Linear Structural Validation application, keeping the setting of the finite element model used for the Topology Optimization (Fig. 8b), including loads and constraints, except for the mesh size.

Figure n.10 shows the stress distribution analysis obtained respectively with Marc (Fig. 10a) and 3DExperience (Fig. 10b) for the Bump loadcase and the finite element model setup on 3DExperience to perform product simulation.

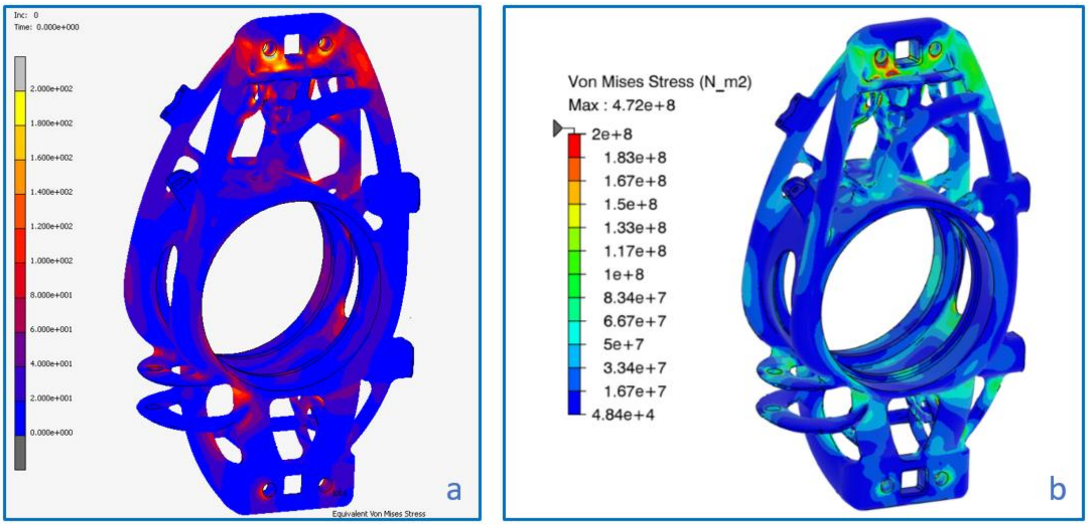


Figure 10: Product Simulation results

Build Preparation

On 3DExperience Powder Bed Fabrication application, firstly setup of the virtual machine environment is required, defining several building parameters related to the manufacturing process (build volume, build tray, scanning type, slicing step, recoating direction, recoating speed etc.). Part orientation can be computed in the same way as Magics, once have set the self-supporting angle, selecting the setup of the optimization to minimize supports. For support generation, vectorial supports from libraries are analogue (see Fig. 11c), but only Wired and Cones can be angled. The design of solid supports is facilitated by the platform environment integration, but the actual use of them is compromised since the interposing of elements between those and the part is possible only for Cone and Tree types. Finally, about 157 supports and a mixed of cones, wired and volume, both vertical and angled have been introduced. Since solid supports are able to support Cones but not Wired, they should be replaced by Wired support type. Additional slicing analysis is required in order to check effectiveness of supporting structures and their refinement. Moreover, the slicing and scan path can be defined, with information about the recoater for powder deposition, the inert gas flow and scanning strategies, patterns and sequences. The generated path can be analyzed so that low melting and roughness points of each slice can be displayed in order to optimize the printing preparation. Figure 11 depicts the industrialized job obtained with Magics (a) and 3DExperience (b).

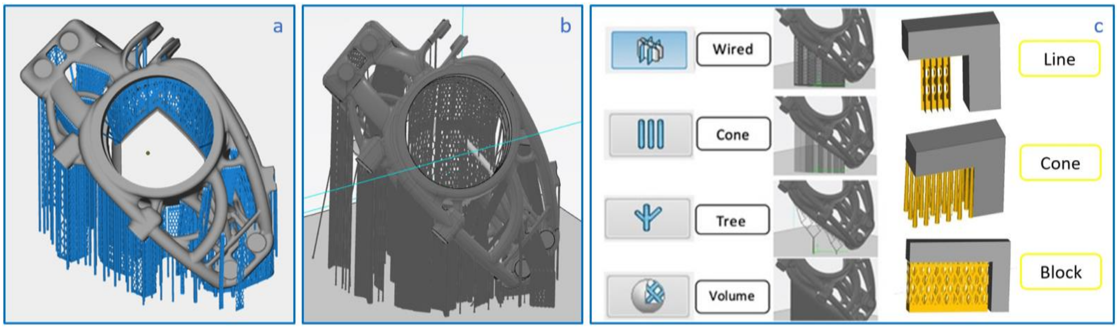


Figure 11: Build Preparation results

Process Simulation

A finite element model is created for part, supports and build tray. The voxel approach is the most suitable processing an STL representation, like the benchmarked one. Specific type of volume and surface mesh are instead the most appropriate working on a model developed inside the platform. Connections between the elements are created, and physical constraints are applied. AlSi10Mg alloy have to be deeply characterized introducing temperature-dependent data for elasticity, expansion, conductivity, specific heat, latent heat, and a plastic law (e.g. Johnson-Cook). A thermal analysis and a structural one have to be set. Process data like the slicing and scanning path are retrieved from Powder Bed Fabrication application. Process temperatures (both for thermal and structural case) of parts, supports and build tray, material deposition information and cooling data (e.g. convection and radiation) have to be specified. Lastly, thermal and structural analysis require proper computation step settings and they finally can be launched. The displacement output (see Fig. 12b) can be exported creating a vector field displacement file, that can be used to obtain a deformed shape starting from the original model using the Virtual To Real Shape Morphing application. This can be analyzed through the Digitized Shape Preparation application to evaluate geometrical displacement on the part after the printing process or, using a best-fit alignment, to measure effective part warping compared to the ideal geometry.

Figure 8a depicts the comparison between the deviation analyses performed on a 3D Point Clouds software (GOM inspect), based on a best-fit alignment with the original CAD model, showing respectively Simufact and 3DExperience results.

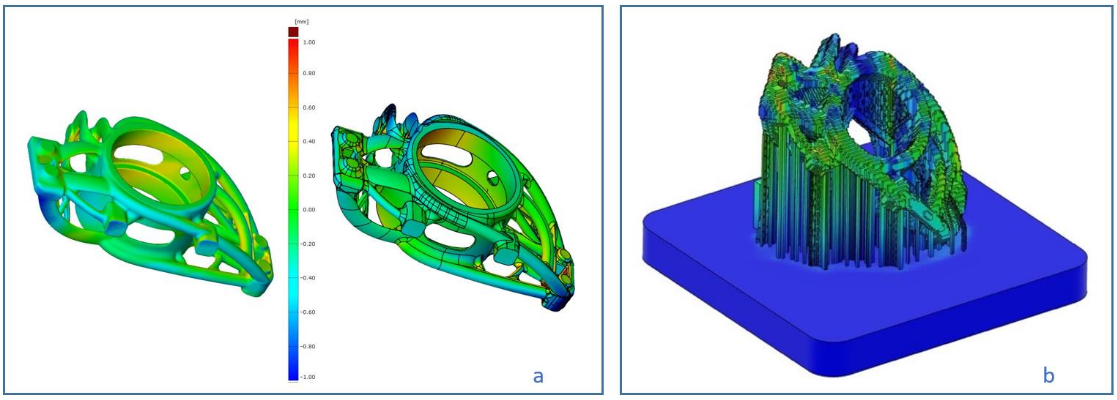


Figure 12: Process Simulation results

Preliminary Discussion

An evaluation based on the results obtained for the each of the local level steps is now presented. The aim is to understand if the several outputs from the local level CAD platform applications can be comparable to the reference ones.

Topology Optimization – Models obtained as output of the computation made in the 3DExperience show features similar to those made in Optistruct referring to the Bump, Cornering and Braking loadcases. For each of them some different elements unavoidably exist, due to the preprocessing interfaces (e.g. RBE elements definition) and the implemented solver’s algorithms. Therefore, despite the need of few differences for model setup, the use of the tool can guarantee likely comparable results. It has to be remarked that the output from 3DExperience can be a solid model instead of a cloud of points and this is easier manipulable for part re-design and optimization.

Product Simulation – Results related to the model static and buckling structural validation performed with 3DExperience and Marc are identical. In the same way as for the Topology Optimization, differences in setup interfaces exist. The biggest advantage of the integrated tool could be the possibility to keep all the settings used to create the finite element model in the topology optimization step.

Printing Preparation – Component industrialization performed with 3DExperience, considering the features differences in the software, could be of course acceptable. Main drawback is the CAD designed solid supports usage which is compromised. Moreover, unlike Magics, the volume support type cannot be angled. Conversely, a benefit is in the re-designs, with the possibility to update model shape and printing preparation keeping information.

Process Simulation – It should be remarked that in the next chapters investigations will be carried out in order to improve the process simulation with the 3DExperience platform. Standard data and general values for parameters will have to be converted into specific ones and experimental phases will be required. Regardless the accuracy of the result, the types of output are of course consistent and comparable. A plus is model meshing type features, a great advantage is the possibility to modify both part shape and printing preparation settings and effectively optimize the printing process. Potential lacks or advantages are highlighted and summarized in Table 3.

Table 3. Platform local level evaluation

Local level Steps	Lacks	Advantages
Topology Optimization	• Preprocessing features to define elements of the finite element model	• Solid models as output of shape computation • Re-design facilitated

Product Simulation	• Preprocessing features to define elements of the finite element model	• Model settings can be retrieved from Topology Optimization
Printing Preparation	• Solid supports not completely effective, not every type can be angled	• Re-design extremely facilitated
Process Simulation	• Not found	• Volume and surface meshing features • Industrialization optimization facilitated

The results will be discussed in chapter 5.

4.2 Product design based on topology optimization

Firstly, few CAD platform based systematic approaches to exploit the design tools potentials are proposed and the approaches variants are discussed. Subsequently, a proper case study is developed in order to validate one of these approaches in the DfAM of a real-case application.

Currently, potentials offered by matching of TO and AM are great, nevertheless, TO tools are continuously evolving since research efforts are focusing on development of additional features and both product-related and process-related constraints, as seen in chapter 2. This is to improve product and process performance and so creating approaches more suitable for AM. Some of the achieved and ongoing challenges concern shape generation and advanced structural features, but most efforts are currently focused on technological and process features integration. Indeed, current tools still show room for development of specific AM constraints. Moreover, it is currently required to perform design interpretations starting from TO results [Reddy 2016] and many approaches have been proposed but automatic smoothing and geometry generation features development is highly desirable. As seen before, operations that compose the design workflow are performed through the use of sundry specific software (i.e. standalone tools), each of them is oriented to a different task. The state of art suggestes that DfAM can benefit from a holistic approach [Plocher 2016] and even tools integration into PLM [Laverne 2014] could provide excellent results, and previous chapter showed how approaches based on CAD platforms (i.e. integrated tools) aiming to integrate product and process design can lead to improvements in DfAM methods application. Moreover, CAD platforms are continuously implementing features that can be exploited in actual design processes.

4.2.1 Systematic integration of TO and DfAM

Product design

With regards to the Product design workflow, hereinafter the description of the general ones, focusing on product development design phase based on topology optimization. The Linear Process Chain (LPC) is the generic approach widely used for common applications. It connects all the already presented fundamental steps, briefly summarized as in Fig. 13. Currently two CAD based steps are involved. The former regards to model preparation for the subsequent optimization (TO); the latter concerns the design interpretation, or rather the construction of a CAD model starting from TO results to be processed for simulation (SIM), validation and further operations. This conceptual general approach can theoretically undergo application, it can be implemented, the design objectives can be met and the design for additive manufacturing can be achieved. Nevertheless, in this way the product design cannot be optimized. In order to do that, at least one re-design loop must be introduced for this purpose.

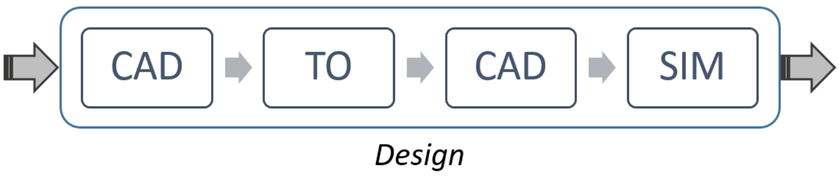


Figure 13: Linear process chain workflow.

Iterative Workflows

Some iterative workflows aiming at optimizing the product including the described tasks have been proposed and detailed [Salonitis 2015, Orquera 2017]. Nevertheless, an abstraction based on the general approach and re-design loops can be described as follows. In order to optimize the product, at least one re-design loop must be introduced and at least one iteration has to be performed. In this way, making use of the cycle, it is possible to optimize the design, nevertheless, it is still impossible to explore sundry conceptual solutions. Aiming to better exploiting potentials offered by AM, it is required to completely re-think products. In order to do that, the exploration of conceptual solutions becomes fundamental and so, two re-design loops can be introduced. Figure 14a and Fig. 14b respectively depict Iterative Workflows with single (IW1) and double (IW2) loop. The red crossed circles identify the decision-making points of the iterative loops.

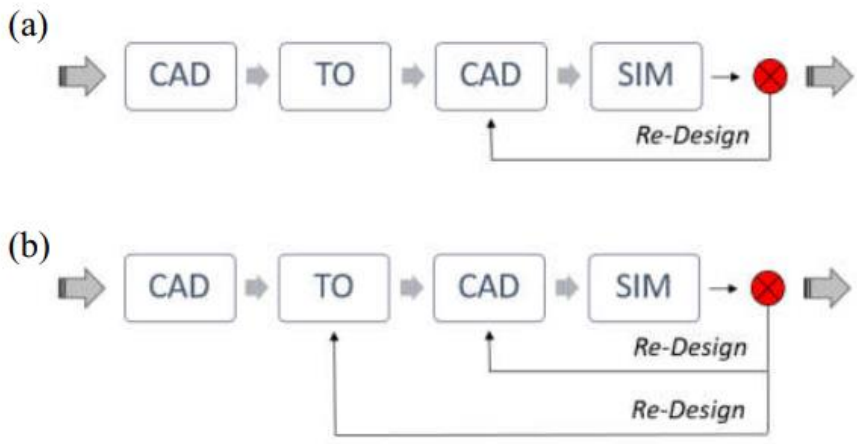


Figure 14: Iterative workflow providing single re-design loop
- IW1 (a) or double re-design loop – IW2 (b).

Iterative workflows are quite widely used in research and development and industrial context on real applications. The main issue is the decision-making point that let to understand what iteration loop to perform: just a re-design loop based on CAD and SIM or to perform a loop that include a new TO, CAD design interpretation and SIM. One possibility can be to measure how results are far from design targets. Nevertheless, the re-design loop selection is ambiguous, and the number of iterations has to be minimized since in particular CAD-based manual geometry interpretations represent highly time-consuming operations. To sum up, the iterative workflow positive aspects are the solutions exploration and the design optimization, while the main drawbacks are related to decision making points ambiguity and reduction of effectiveness of the method with respect to minimization of product development lead time.

DfAM SYSTEMATIC APPROACHES

The approaches that provide a systematic organization for DfAM are those that clearly state *when* and *why* each re-design loop occurs. The focus is moved here to describe those approaches. Moreover, possible benefits with respect to key factors have to be considered and evaluated. A remark is that, despite general approaches can be implemented with use of any combined standard tools, for succeeding approaches some specific features which are offered only by integrated tools may be required.

Systematic Enhanced Design –based

First model can be highly improved in order to both accelerate the product development process and deeply exploit TO. Figure 3a depicts the Enhanced Design Refinement –based (EDR–based) approach. By using integrated tools that let to automatically generate geometries from TO results (such steps are hereinafter defined as A-CAD in diagrams) which can directly undergo validation, it can be possible to start from these to obtain results of simulated behavior of components. Then, it is possible to limit manual modification just for the loop that concern the Design Refinement for product optimization (see Fig. 15a). A variant of this approach can provide an additional loop between TO and the relative result, again by making use of automatic generation of model geometry (see Fig. 15b). This method can lead to advanced design and so it becomes possible not only to perform a Design Refinement, but also a TO Refinement. It suits excellently with design of large structures (e.g. chassis applications) since its enables optimal shape generation while containing computational costs due to advanced model discretization (mesh resolution) and additional computation constraints.

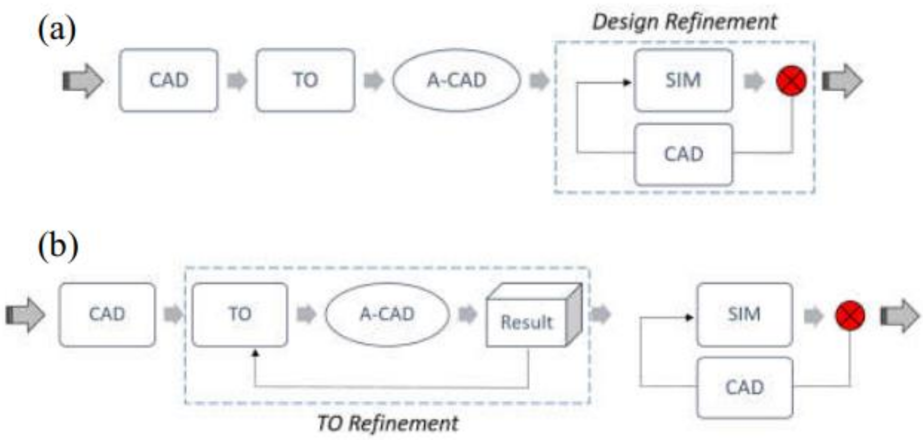


Figure 15: DfAM systematic approaches: enhanced design refinement–based (a); enhanced design and to refinement–based (b).

However, both the methods can find application mostly through integrated tools such as CAD platforms. They can be thought as an extension of the first iterative workflow, based on advanced tools in order to bring advantages to the approach such as confinement of the design refinement limiting manual CAD operations and speeding up the design process.

An example of the Enhanced Design Refinement –based approach is the steering upright redesign provided in chapter 4.1.2

Systematical Design Methodology –based

Another approach that not only lets to optimize the design in a fast and effective way, but also lets to embrace the study of different conceptual solution can be the Systematical Design Methodology –based (SDM–based), described as follows. Guidelines for systematic design suggest to split the design steps into: a conceptual phase to generate solutions; an embodiment phase to structure the layout; a detail phase to create ultimate designs. Referring to the steps defined by conventional systematical design methodologies, the iterative cycles can be distinguished by positioning them into the design levels, as depicted in Fig. 16. In particular, once have selected TO for concept creation, a first loop can concern the concept development, whereas a subsequent one can be focused on the result refinement relative to the embodiment design phase to create the preliminary layout and the detail design phase to obtain the final models.

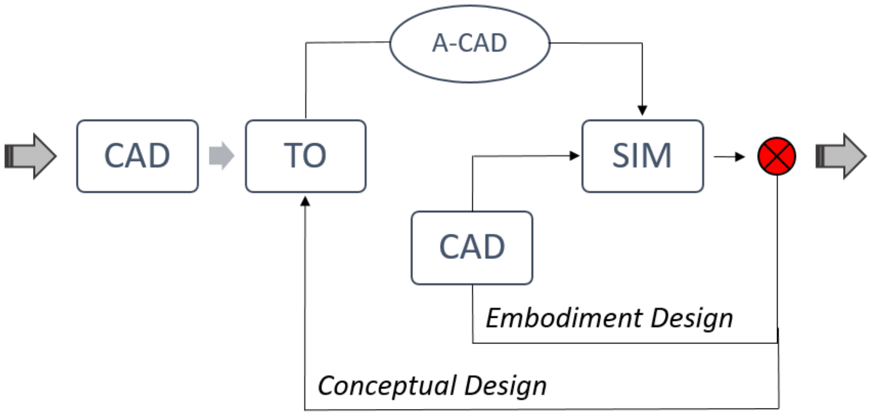


Figure 16: Systematical design methodology–based approach.

By making use of integrated tools that enable the automatic generation of the geometry starting from TO results, the feature can be exploited in order to evaluate different conceptual solutions and finally move to manual CAD re-design just for the solution that underwent the previous design steps. In this way, solution exploration, result optimization and method effectiveness involving re-design minimization can be joined together by creating a structured approach. Introduction of systematic design together with adoption of integrated tools can thus provide many benefits to the general approach providing re-design loops.

Systematic Concept Selection–based

Another approach can be the Concept Selection –based (CS–based) one depicted in Fig. 17, which is focused on facilitating the exploration of possible solution while introducing at the same time structured systems for concept selection.

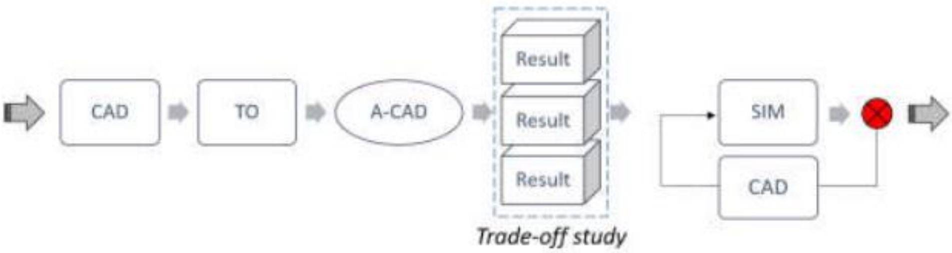


Figure 17: Concept selection–based systematic approach.

A traditional approach could provide the use of spreadsheets to collect data relative to different analyses on product and to create comparison matrices for concept selection based on KPIs. Alternatively, classic standardized tools from systematical design methodologies can be used for the product development. By making use of integrated tools that join automatic generation of geometries starting from TO results and moreover PLM integration (keeping data about analyses and simulations of products), the conceptual design phase can be considerably speeded up. Some integrated tools additionally let to manage the data inside the platform and to integrate the decisional process into the optimized component development environment. Finally, just one iterative re-design loop for Design Refinement is introduced. In this way, the CS-based systematic approach that integrates trade-off studies can be depicted as in Fig. 17. In particular, it is possible to observe that different TO results representing conceptual solutions can be involved in such type of Trade-off studies for selection. This type of approach, in which solutions generation becomes driven, leads to embracing the space of generative design. A remark is that this type of approach is strictly based on integrated tools providing proper features.

RESULTS

An overview of the results related to the approaches described before is presented here, with regards to some of the analyzed key factors. Moreover, a subchapter explains how current methods can evolve in order to improve their effectiveness. In particular, forthcoming scenario is analyzed, including advances in generative design to support the DfAM.

A qualitative assessment on the base of the elements discussed in the paper is provided. Except for lead time reduction, a non-subjective evaluation on the presented methods is performed. This concerns the possibility or impossibility to perform the analyzed features. Table 4 shows features of general and systematic approaches. Starting from summarized results, systematic approaches clearly can bring benefits to the DfAM method in particular for product optimization capabilities, design exploration of conceptual solutions and reduction of product development lead time. In particular, it emerges that a linear-type process is the less advantageous with respect to the considered elements. Also, it can be observed that SDM and CS approaches obtain the highest scores. Nevertheless, SDM has the advantage of having a clear loop selection due to the systematic design implementation, whereas CS has the advantage on concept solution selection, due to the structured proper tool. Moreover, a remark is that use of generative design means together with development of tools integration could bring additional effective improvements to DfAM.

Table 4. Presented approaches and key factors.

Key factors	General Approaches			Systematic Approaches		
	LPC	*IW1*	*IW2*	*EDR Based*	*SDM Based*	*CS Based*
Design for AM	+	+	+	+	+	+
Product Optimization	–	+	+	+	+	+
Design Exploration	–	–	+	–	+	+
Concept Selection	–	–	–	–	–	+
Loop Selection	–	–	–	–	+	–
Lead time reduction	–	–	–	+	+	+

Systematic Product design for DfAM challenges

Hereafter the forthcoming prospective concerning DfAM approaches including TO is discussed. In this compound, Generative Design –based (GD–based) approaches are gaining a growing interest. By the development of generative design tools and integration of the techniques into the DfAM approaches, not only geometry creation process but also conceptual studies setup can be automatized. Great potentials concern mostly solutions exploration and product development lead time reduction. Generative Design could fasten creation of conceptual solutions, by including different design and manufacturing constraints and providing directly CAD models. It becomes even possible to compare solutions relative to different manufacturing processes, but in particular for AM there could be great room for improvement. It might represent the optimal solution for design automation needs demonstrated by Wiberg et al. [Wiberg 2019], but actually there is wide room for improvements. Presented approaches are mainly focused on product whereas the real challenge should be the simultaneous integration of product and process optimization.

Currently, it is still necessary to interpret design and add further studies considering build direction, overhangs, supports and build time by using additional tools and personal experience. Furthermore, multi-objective optimization problems might be introduced, combining for example for product optimization TO and parametric optimization, or introducing features for anisotropic materials, multi-materials, functionally graded materials. Moreover, multi objective optimization could include printing preparation integration in the design phase with process information and characterization, aiming at minimizing also supports, build time, costs [Reddy 2016 Wiberg 2019]. Finally, the most challenging feature could be the integration of tools for process simulation, in order to add to economic analyses also feasibility validation and quality prediction (e.g. part defects, stress, warping) and to improve the DfAM process [Reddy 2016, Plocher 2016].

The results related to the systematic approaches will be discussed in chapter 5.

4.2.2 Case Study for Product design based on topology optimization

The presented work aims to detail and validate the application of the the **Systematical Design Methodology –based** approach focused on product optimization. A racing automotive brake caliper has been re-designed to be produced by Selective Laser melting (SLM) AM, with performance improvement objectives, through the application of a systematic CAD platform-based approach. The iterative design refinement required to obtain final models and Technical Product Documentation (TPD) is described on a real-case application, and the DfAM approach is analyzed.

The tool involved to implement the approach is the 3DExperience CAD-based platform for product/process design. The platform is based on Catia CAD environment, Simulia CAE tools for topology optimization (Tosca) and simulation (Abaqus).

The method through the redesign is achieved was described in chapter 4.2.1.

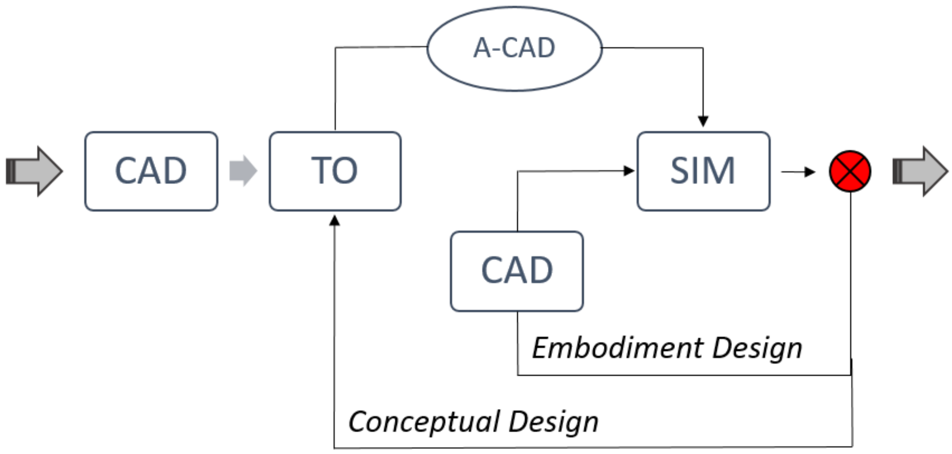


Figure 18: Systematical design methodology–based approach.

Case Study

Components of racing cars are usually subjected to combined stressing factors and in particular braking systems can have issues in use, as they have to work with intense loads at high temperatures [Limpert 1999]. A commercial Formula SAE brake caliper, originally made by CNC milling of Ergal 7075-T6 aluminum alloy, reached temperatures close to 300 °C with problems of strength and deformation, so it has been re-designed to be printed by SLM process. Sergent et al. analyses [Sergent 2014] show critical conditions for a working brake caliper from a structural point of view and how topology optimization let its performance improvements. Travi Farias et al. work

[Travi Farias 2015] shows how its thermal management is fundamental, since at high temperatures materials mechanical properties decline. Moreover, the study states that AM enables the construction of complex geometries that can increase model surface/volume ratio and facilitate heat dissipation. Bugatti’s full developed case [Wischeropp 2019] demonstrates with experimental testing how titanium alloys use is feasible and leads to performance improvements. Lately, other cases can be found in [Vasseljen 2018, Tyflopoulos 2021] Nevertheless, none of these cases is based on an integrated design approach, whose possible potentials have been previously discussed. Referring to the general workflow , the Product Planning and Design tasks are now described.

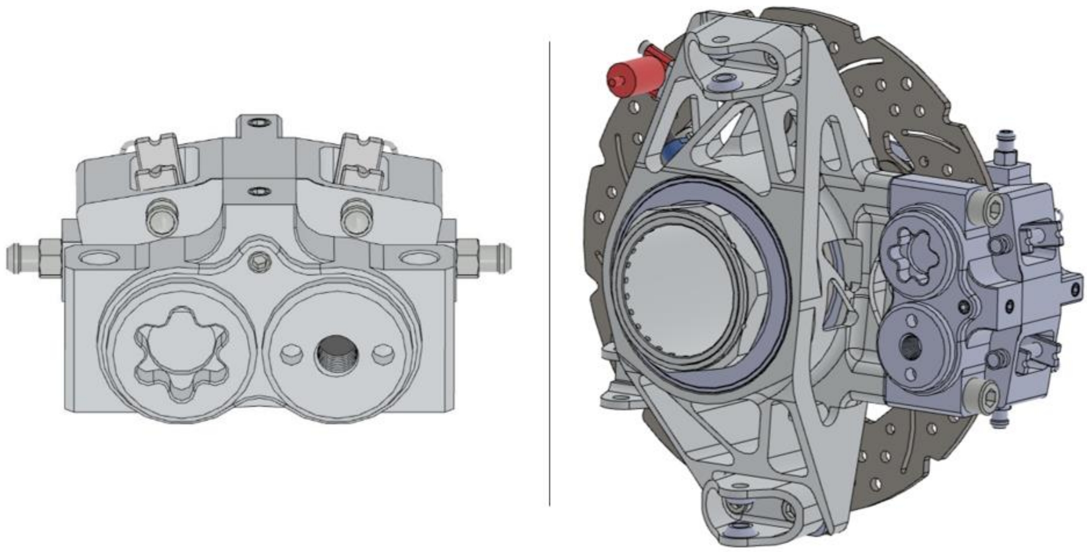


Figure 19: The original CNC milled brake caliper

Product Planning

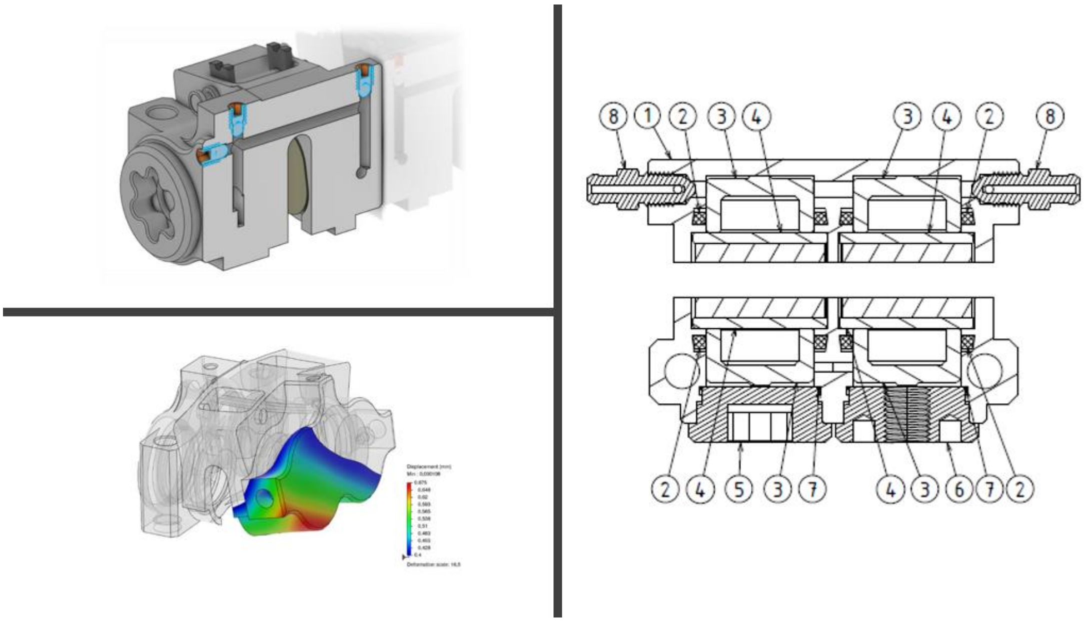


Figure 20: The analyses on the original component to set the design specifications

The analysis of the commercial component is the starting point of DfAM with the aim to define the design features that provide the same working behavior. In particular, that concerns mostly the fluid-dynamic of oil channels. In addition, a make/buy decision step leads to keep standard and commercial elements of the original part, whereas the body and pistons are re-designed. Since original 2D drawing is not available, functional features have been measured by metrology equipment to define the coupling tolerances. Data about mechanical and thermal loads acting on the part have been collected via experimental measurements and analytical models from the vehicle dynamics. Maximum pressure on the oil circuit is 100bar and tangential load for maximum brake torque at the disc brake is 14kN. Temperatures reach on average about 200°C with maximum peaks close to 300°C. An analysis on the assembly of the front wheel group has been done in order to define physical design constraints related to part fitting, coupling and working. Based on that data-set, FEA of the original caliper returns the structural targets for the project, such as improvement of stiffness at high temperature and weight reduction. A fundamental step is material selection, according to datasheets related to SLM. Since mechanical properties of 7075-T6 alloy suffer of significant drop at high temperature, Ti6Al4V titanium alloy is selected. According to literature data, compared to 7075-T6 alloy, it presents, at working temperature, about 11% higher Young's-modulus/density ratio and even 45% higher yield-stress/density ratio. Moreover, manufacturing analysis, with machining and specific heat and surface treatments is required. Product Data are collected in the Requirement List. The DfAM goals consist in the use of Ti4Al6V to better resist at high temperatures and a topology optimized shape to save weight. An opened and branched geometry can also increase surface/volume ratio with benefits for thermal management in terms of heat dissipation.

Mechanical Properties	Test Method	As Built	Heat Treated
Tensile strength	ISO 6892-1:2009(B) Annex D	1200 ± 40 MPa	1050 ± 30 MPa
Yield Strength (Rp 0.2%)	ISO 6892-1:2009(B) Annex D	1100 ± 50 MPa	950 ± 30 MPa
Elongation at Break	ISO 6892-1:2009(B) Annex D	8 ± 3%	Min. 6%
Young's Modulus	-	110 ± 15 GPa	115+20 GPa
Hardness	DIN EN ISO 6508-1	34 HRC	34 HRC

Thermal Properties	Test Method	As Built	Heat Treated
Max. Long Term Operating Temp.	-	350° C	350° C

Figure 21: The mechanical properties of the Ti6Al4V alloy for L-PBF

Design

Initial step of the Design phase is the DS modeling. It starts from the input data of part and assembly analysis in order to define the maximum volume available for the TO computation. Most functional elements should be removed whereas features for part connections and main couplings must be kept (pistons, brake pads and pins housings, bolt holes, caliper caps) in order to constrain the region. Wheel rim radius, encumbrance of wheel knuckle and brake disk or parts assembly trajectories are also required. NDS volumes must be defined in order to insert regions to keep material, such as bolts holes or internal features.

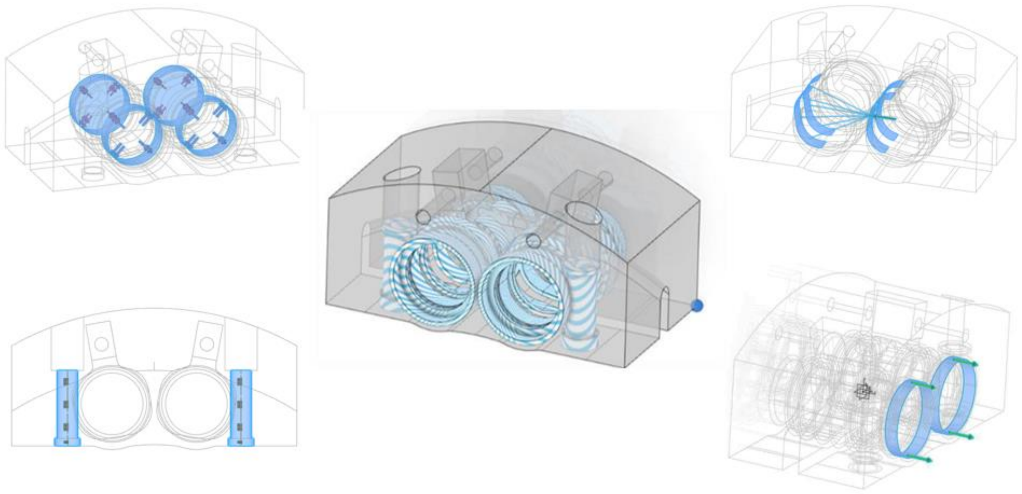


Figure 22: The design space and the loadcases definition for the finite element model

The second step is the setup of FE model in order to run optimizations and analyses. Hinge restraints are applied for the screws. Maximum 14kN tangential load (due to braking torque) is applied on a node put on the disk brake midplane, connected to contact surfaces (RBE3) of braking pads. Maximum 100bar oil pressure is applied on internal surfaces of pistons housings and equivalent calculated reacting forces of 9.8kN are applied on the thread regions of the caliper caps. Material is created using parameters for build direction (due to AM alloy anisotropy [Simonelli 2014] in favor of security. Discretization of the design space is made by a 1.5mm tetrahedron (TL4) mesh and refinements. A preliminary static analysis on the design space is run to validate the model setup and check its stiffness (ideal maximum value). TO is setup with target mass reduction and minimization of compliance.

A conceptual iterative design exploration with a symmetry constraint study and a computational refinement is performed. That geometry makes the right and left parts become the same and reduces the modeling to half-body, with potential benefits of design and production time and costs. The results are used to create solid models through improved smoothing conceptual shape generation. These see directly ProdSIM by FEA, showing that an asymmetrical design plain brings better performance in terms of maximum displacement. Fig. 23 shows TO results C1 and C2.

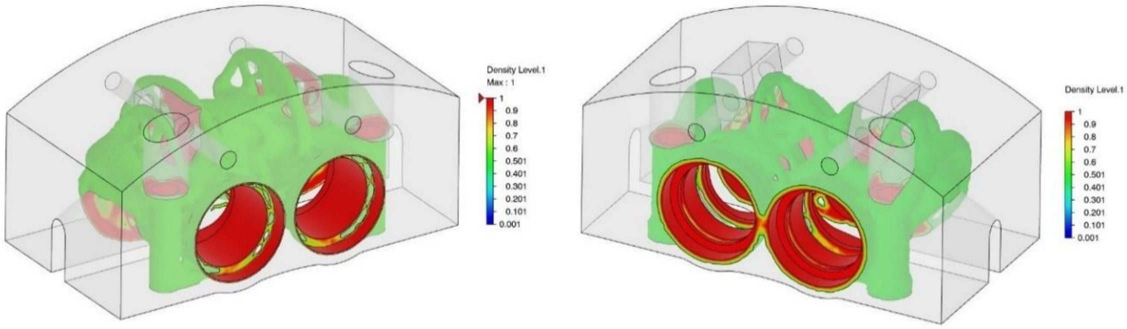


Figure 23: From left to right, conceptual results (C1, C2) and designs (V1, V2, V3)

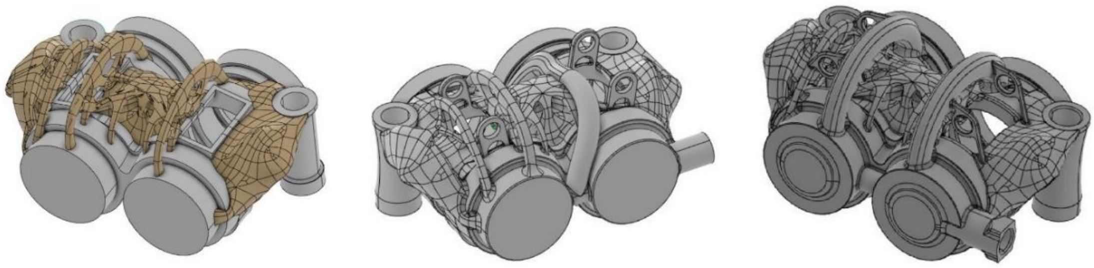


Figure 24: From left to right, conceptual results (C1, C2) and designs (V1, V2, V3)

Once the TO is finished, an embodiment iterative design starts to improve part shape. The Design Interpretation occurs, modeling the functional geometry with surface design and the branched shape with free-shape design. Moreover, oil channels are introduced and used to contribute to part stiffness working on their shape and position. ProdSIM by FEA is necessary to predict part deformation and stress. Last two refinement cycles involve the detailed design of each part housings (gaskets, o-rings, valves, pins) and the implementation of DfAM guidelines for internal features (self-supporting cross-sections of channels) and the branched shapes (thickness, supporting angles), according to part orientation planned for construction. After validation, results of manufacturing analysis are used to create the raw part model and the final drawings (TPD).

Results

For static load validation, yield stress at 220°C is considered, with value for build direction (Z) and an additional safety factor 1.2 (racing application), so permissible stress of 560MPa is calculated. Fig. 25 shows results. Moreover, remark on fatigue life and proper processing/treatments on stressed areas is necessary [Denti 2019].

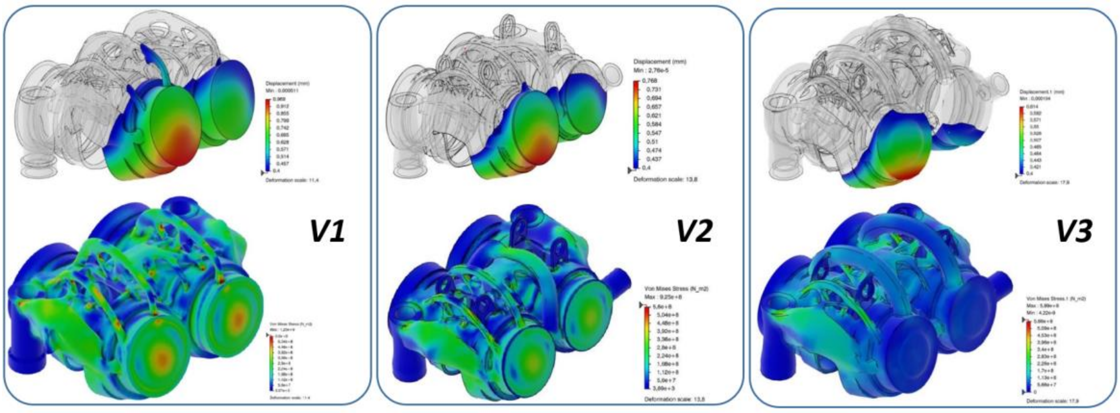


Figure 25: Displacement and stress of V1, V2 and V3.

As reported in Tab. 1, maximum displacement at 220°C is 0.675mm for the original caliper and 0.614mm for the final design of the optimized one (9% reduction) while the body weight goes from 248g to 184g (25,8% saving). Moreover, an analytical thermal study of a braking cycle by Matlab code shows a 20°C decrease of working temperatures for the final design. One last note is that titanium has worst tribological characteristics (low wear resistance and high seize tendency) and thus surface treatment chemical nickel-plating (Niplate) for pistons housings has been defined. Cold and hot tolerances for couplings are re-calculated.

Table 5. Comparison between designs.

	Original	V2	V3
Weight [g]	**248**	**176**	**184**
Weight reduction [%]	**-**	**-29.03**	**-25.81**
Displacement @220°C	**0.675**	**0.768**	**0.614**
Deformation reduction @220°C	**-**	**+13.78**	**-9.03**
Displacement @20°C	**0.555**	**0.694**	**0.551**
Deformation reduction @20°C	**-**	**+25.05**	**-0.72**

Iterative design refinement

The iterative design refinement is now synthesized. Loops for product optimization, each of them performed in the integrated CAD platform, can be outlined at different levels. First loop includes Topology Optimization, A-CAD and Product Simulation and produces conceptual solutions (C1, C2). Automatic tools for design interpretation are used and loops are made fast thanks to the integrated platform. Second loop includes CAD and Product Simulation and let the development of embodiment solutions (V1) or definitive ones (V2, V3) adding elements of the detail design. Design requires manual (time-consuming) geometry interpretation only for first iteration, whereas re-designs are extremely facilitated by the integrated environment for the subsequent ones.

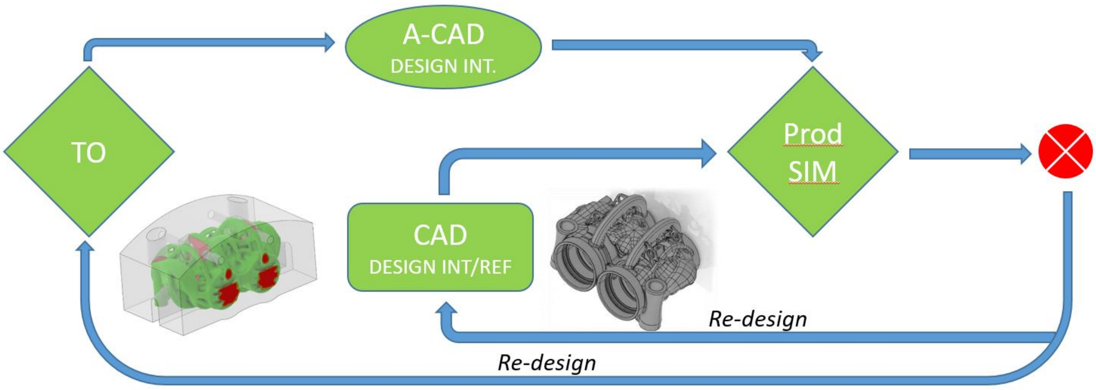


Figure 26: The application of the systematic approach for the redesign of the brake caliper to identify the two main loops

4.3 Process design based on simulation

Firstly, a design method to optimize the process is proposed. Two preliminary studies are presented in order to firstly validate simulation implementation feasibility through a CAD platform and then to validate simulation results compared to experimental data for further method application.

Laser-based Powder Bed Fusion technique is considered in this work and the implementation and validation of the Selective Laser Melting process simulation is performed in order to support the method. *The aim is therefore to minimize process-induced defects and flaws of AM-based manufacturing of metal products, such as residual stress and distortions. The approach consists of industrialization task improvement based on modelling optimization and build optimization sub-phases supported by numerical process simulation. Integration of CAD platforms allows embedding these steps to be performed downstream of the product design.*

AM industrialization operations are generally thwarted by the use of sundry specific tools (CAD, CAE, CAM, etc.) to perform required operations that compromise data consistency (chapter 2). For example, tessellated representations used to set up a build job cannot be directly manipulated, and this leads to non-reversible steps. As a consequence, re-design loops necessary to achieve product and process optimization become difficult and entail increased product development lead time. The use of integrated platforms for product/process design can be exploited to link tasks and operations, using parametricity, associativity, and information retrieval introduced by a CAD-based environment.

4.3.1 Integrated process optimization design method

Process optimization can be achieved by working on industrialization, with the optimal process design intent. In this case, process design optimization is obtained by introducing process simulation as a key element to drive few re-design loops. Development of design methods based on processing simulations can represent an optimal solution for DfAM [Vaneker 2020]. By adopting a CAD-based platform for product/process design, the generic industrialization workflow can be implemented, and we can support integrated optimization loops. Data related to systems, products, and processes can be linked together and retrieved for all steps, and thus, starting from process simulation results, we can drive process design on two main loops (Fig. 27):

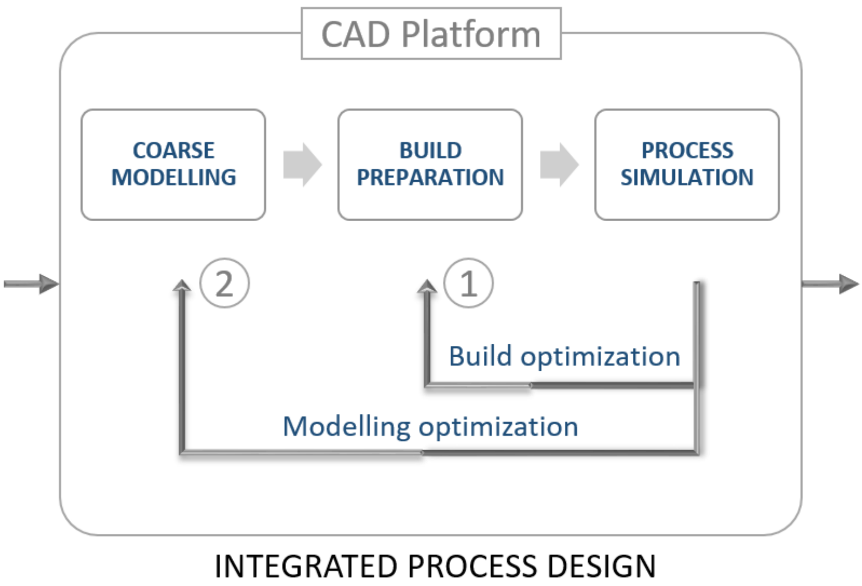


Figure 27: Integrated process design method

- Modelling optimization - Simulation results can be used to operate on coarse modelling, directly working on features tree and parametric entities to regenerate parts shape of CAD models.

- Build optimization - Simulation results can be used to operate on build preparation, working on printing parameters and layout settings, to regenerate the CAM build job.

Each study conducted in integrated environment benefits of associativity and information retrieval, so that each modification can be directly validated through the CAE process simulation. Therefore, a process design can be easily improved to reduce possible process issues such as defects and flaws through suitable support of simulation data. Such simulation based procedures allow to implement strategies to reduce shape defects related to PBF process [Alfaify 2020]. In particular, they make possible to act on layer geometry, part orientation and support structures, that represent some of the main impact factors on residual stress [Luo18] and parts deformation. To sum up, it is possible to control them to minimize components deformation by operating on both modelling phase of components and preparation phase of 3D printing job.

In order to support this work previous preliminary studies on process simulations are required. Firstly, a study on simulation setup considering specific steps, results type, workflow feasibility, and suitability for the method was conducted (Chapter 4.3.2). Secondly, a study focused on numerical results accuracy compared to experimental results was performed to validate predictive approaches. The study performed on a cantilever beam concerned thermos-mechanical process simulation, specimen construction, measurements (Chapter 4.3.2).

Since the proposed method is based on the use of a CAD platform, the tool selected to develop and validate the industrialization phase is the DS 3DExperience platform.

The results on case studies developed to evaluate feasibility and accuracy of simulations and relative results are described in the next section.

4.3.2 Qualitative and quantitative validation

Two case studies (CS1, CS2) produced by SLM process using an SLM 280 HL machine are presented. These are necessary to perform qualitative evaluation on operations to support the method and quantitative evaluation on simulation predictive reliability. CS1 (Fig. 27a) is an automotive component used to validate the DfAM approach based on integrated CAD platforms [13]. CS1 was designed through topology optimization techniques and subsequently it was built (Chapter 4.1.1). CS1 has been used to evaluate the simulation feasibility and to validate the type of operations and results required to perform a process optimization. CS2 (Fig. 27b) is a cantilever beam, that is a widely investigated type of specimen [Li 2017]. It has been used to deeply work on process simulation and results compared to experimental data. CS2 has been modelled and subsequently two specimens have been printed respectively oriented along X and Y directions, while using uni-directional scanning strategies oriented along X. Finally, measurements have been carried on to evaluate deformation magnitude and these have been used to validate simulation results.

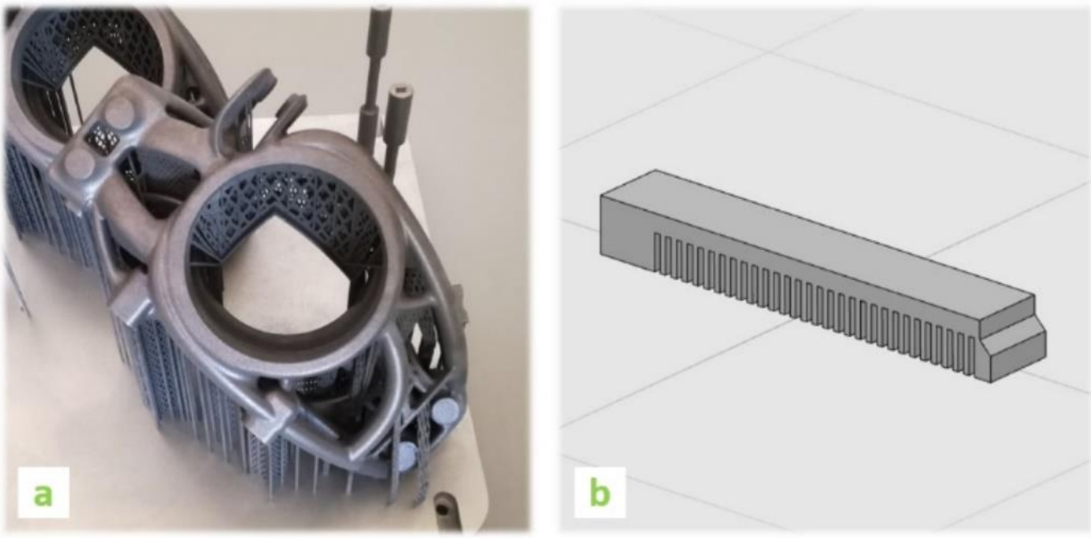


Figure 27: 3D printed CS1 (Steering knuckle, (a)) and CS2 model (Cantilever , (b))

Case study CS1

CS1 represent the first step for simulation implementation. In order to evaluate simulation feasibility and validate type of output results, the aims are to:

- Obtain the setup required to correctly run a complete thermo-mechanical process simulation
- Obtain maps of the residual stress and displacement fields distribution at the end of the process
- Obtain vector fields related to nodal displacement to be used to deform the model
- Evaluate how to apply these results to the model in order to compensate deformations induced by the printing process

Case study CS2

CS2 represent the second step. In order to deepen simulation and to validate relative results compared to experimental data, the aims are to:

- Obtain the setup for the printing process simulation and also for the further post-processing phases of supports cut and specimen removal from the buildplate
- Obtain maps of the displacement fields distribution once the residual stress release phenomenon is simulated
- Evaluate the accuracy of simulation results including post-processing operations

Selective Laser Melting simulation

The simulation approach is currently the complete thermal and mechanical weakly coupled computation, with moving heat source defined by the scanning path strategies setup.

Regarding CS1, since we had already designed and built the component, the input data are the tasselated geometries of the programmed 3D printing job. The setup of a virtual machine into the printing preparation environmnent is required to replicate its physical features. It is necessary to set build volume, buildplate, scanning type, slicing step, recoating direction, recoating speed. Subsequently, the slicing and scan path can be defined, with information about the recoater for powder deposition, the inert gas flow and scanning strategies. A finite element model is then created using a voxel mesh, and elements are linked with proper connections. Initial material characterization is retrieved from library and some modifications regarding temperature dependent data (elasticity, expansion, conductivity, specific heat, latent heat, and a plastic law) are done according to literature. Thermal and structural analysis computation steps are set and simulation can run.

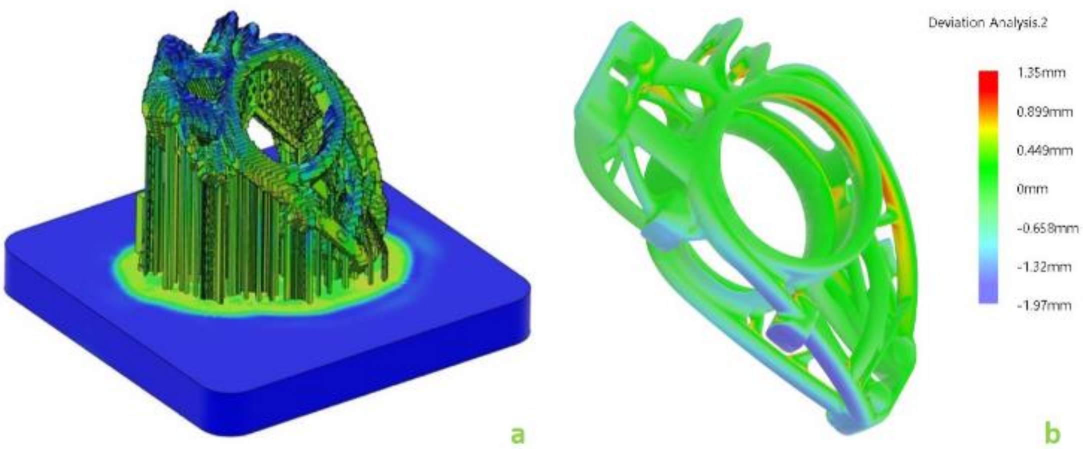


Figure 28: Output data of process simulation (residual stress field, (a)) and deviation analysis from output data (original model and deformed model overlapping, (b))

Fig. 28a shows the map of the residual stress field after the printing process. Such type of output is suitable as indication to work on printing preparation tasks. Fig. 28b shows a deviation analysis between the deformed part and the original one performed into the CAD environment. The deformed model has been obtained by exporting nodal displacement into a vector field CSV format and by applying it to the original one. While traditional modelling approach is granted, this procedure confirms even the possibility to compensate process induced deformations.

Regarding CS2, for the evaluation of process induced residual stress and subsequent deformation due to its release, we refer to the following experimental data. The measurement of the maximum deformation along Z (Max. Z distortion) after specimen/supports removal has been considered. Measurements are taken using an optical microscope Kestrel (Vision Engineering) with encoder resolution o 1µm. 15 points have been detected on the deformed specimen and 15 points have been taken on the standard steel truss. Max. Z distortion is obtained through the difference between the higher dot on the curve (Max. Z height) and the height of the non-deformed specimen.In order to set the simulations, phases aforeseen are performed in sequence starting from cantilever modelling and retrieval of machine and its setup. To program the 3D printed job, after parts positioning, the uni-directional scan paths along X direction are defined. Main parameters such as laser parameters, scanning parameters, layer thickness and operating temperatures are specified. Tab. 1 collects the main process parameters used for tests. For exact computation of residual stress and deformation behavior, a deep study on material characterization and process parameters is mandatory, since they highly affect results.

Table 6: main process parameters

Laser diameter	0,1 mm
Laser speed	1,15 m/s
Laser power	275 W
Hatch distance	0,17 mm
Layer thickness	50 µm
Gas flow	4,17e-5 m^3/s
Chamber temperature	50 °C
Buildplate temperature	150°C

First simulation procedure is setup to return a deformation field consistent with respect to 3D printing and subsequent complete part removal from the buildplate. Tab. 2 returns the value of experimental measurement of Max Z distortion for the X specimen (Fig. 29a).

Figure 29: Deformed X specimen from 1st test after removal (a) and 3D printing job layout from 2nd test (b)

Table 7: 1st test measurements

Specimen	Max Z distortion
Cantilever along X direction	1.846 mm

The simulation approach provides the thermal and the structural case to be set up. After that, a simulation step for the printed job cooling at environmental temperature is introduced. Finally, the builplate mesh is removed and the constraints are switched from the buildtray to the specimen. Simulation results (Fig.30) are quite coherent with respect to experimental data.

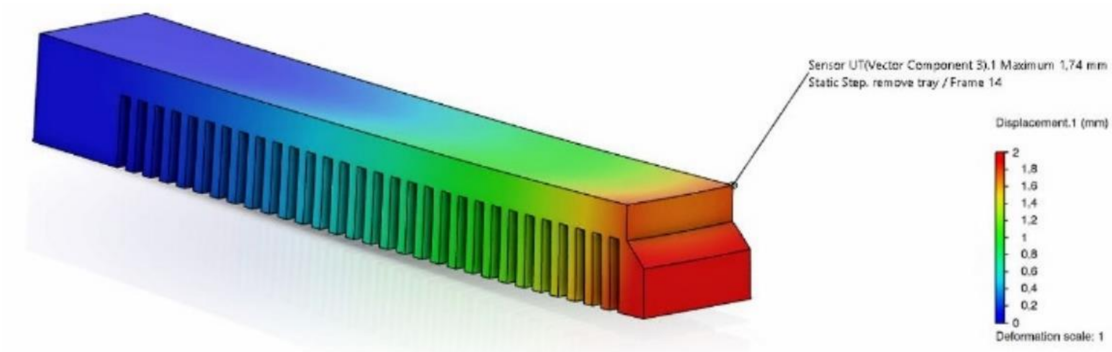


Figure 30: Displacement field map of X specimen from 1st test after removal

X specimen Max. Z distortion simulation result is 1.74 mm. Absolute error is 0.11 mm which corresponds to 5.74% percentage error. Fig. 31 shows the measurement procedure performed into the CAD environment. It is based on the creation of the deformed model (by applying the vector field CSV) to be overlapped with the original one and toe evaluation of Max. Z height and Max. Z distortion.

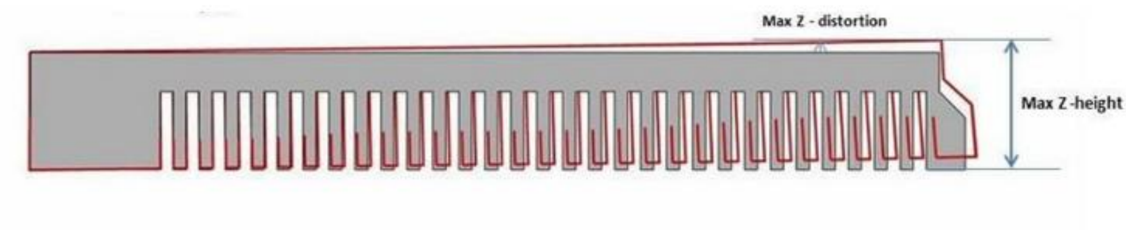


Figure 31: Maximum Z distortion calculation method

Second simulation procedure is setup to return a deformation field consistent with respect to the 3D printing and subsequent support cut phase. This simulation is related to construction and subsequent measurements of both X and Y specimens, whose job layout is depicted in Fig. 29b. Tab. 3 returns the values of experimental measurement of Max Z distortion for the X and Y specimens (Fig. 32).

Table 8: A summary of the setup for the process and post-processing simulation

Thermal analysis	
Chamber temp.	323.15 K
Buildplate temp.	423.15 K
Convection coef.	22.3 W/m^{2}K
Emissivity	0.36
Time step	4000 s

Mechanical analysis	
Chamber temp.	323.15 K
Buildplate temp.	423.15 K
Time step	4000 s
Clamp restraint	Buildplate lower surf.

Cooling	
Prescribed temp.	298.15 K
Time step	7200 s
Clamp restraint	Buildplate lower surf.

Buildtray removal	
Time step	1 s
Translation constr.	X,Y,Z Buildplate lower surf.
Mesh deactivation	Buildplate mesh
Clamp restraint	Pillar lateral surf.

Supports cut	
Time step	1 s
Clamp restraint	Pillar lower surf.
Mesh deactivation	Buildplate and supports

Table 9: 2nd test measurements

Specimen	Max Z distortion
Cantilever along X direction	1,14 mm
Cantilever along Y direction	1,03 mm

This work represents a further step to simulate the effect of uni-directional scanning strategies along X direction and post-processing operations. In this case the simulation approach is based on the same operations as the previous case, except for last two steps. Optimal simulation setup firstly provides the elimination of the buildplate and the constraint switch to the specimen, then the elimination of mesh layers corresponding to supports cut and finally clamping on the specimen bottom surface to replicate the buildplate connection preservation. Simulation results (Fig.32) are coherent compared to experimental data.

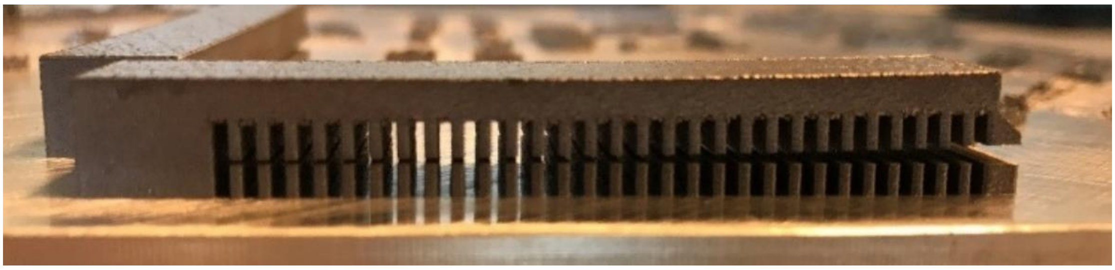


Figure 31: Deformed X specimen fom 2nd test after supports cut

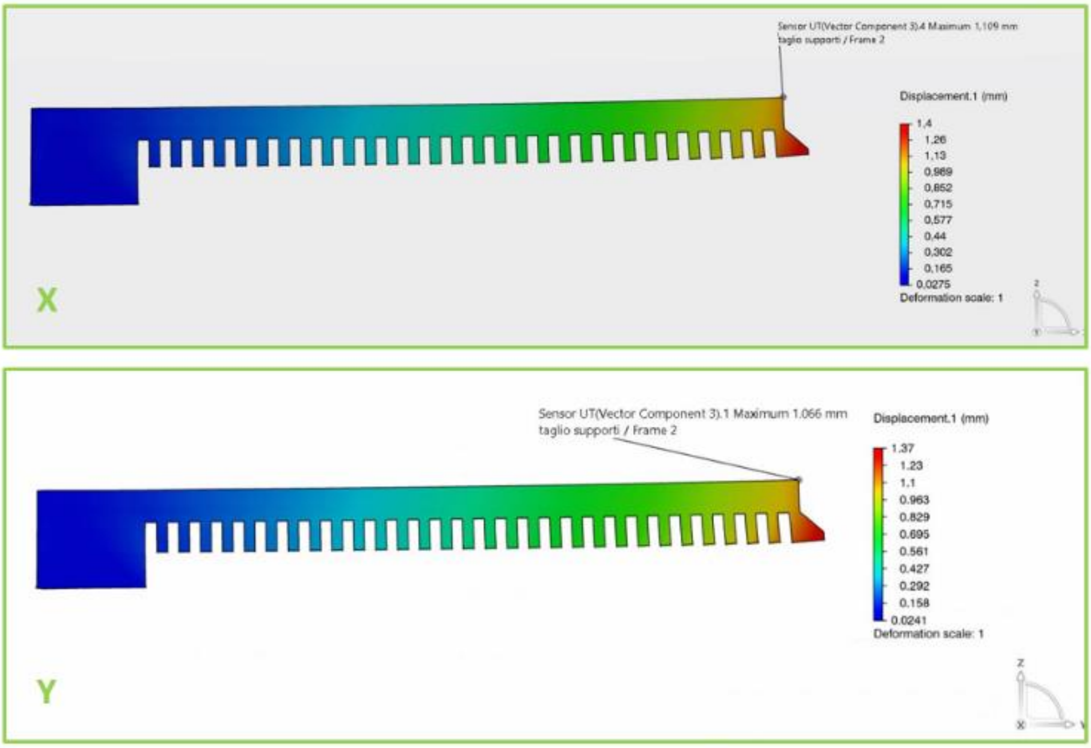


Figure 32: Displacement field map respectively of X and Y specimens from 2nd test after supports cutting

X specimen Max. Z distortion simulation result is 1.11 mm and experimental measure is 1.14 mm. Absolute error is 0.03 mm which corresponds to 2.63% percentage error. Y specimen Max. Z distortion simulation result is 1.07 mm and experimental measure is 1.03 mm. Absolute error is 0.04 mm which corresponds to 3.88% percentage error.

A remark on results accuracy is relevant. An optimal complete thermo-mechanical simulation should be based on element size at most equal to laser spot dimension 0.1mm [Luo 2018]. For computational cost issues, a thermomechanical simulation lumping few layers has been adopted, that is based on element size of 0.25x0.54x0.54 mm (it discretizes 5 layers and 2 laser paths). Further studies have to be focused on the exact effect of scanning strategies on computed results and the simplified models application to reduce computational cost.

The results of qualitative and quantitative validation will be discussed in chapter 5.

4.3.3 Case Study for Process design based on simulation

The process optimization design method is applied to perform the industrialization phase of a high-performance automotive component. The case study is a formula SAE topology optimized brake caliper to be produced by Selective Laser Melting (SLM) process. Process simulation-driven studies on modelling and build preparation subphases (i.e. orientation definition, supports generation, model distortion compensation) are conducted to support the process design. The study demonstrates the part scale level method's suitability to industrial context to improve industrialization in the redesign of components to be produced by metal AM.

The presented method is then applied to the DfAM industrialization phase of an automotive case study. A build optimization study and a modelling optimization study are performed.

The tool involved to implement the approach is the 3DExperience CAD-based platform for product/process design. The platform is based on Catia CAD environment, embedded with Delmia CAM tools for process design and Simulia CAE tools for FE simulation (Abaqus code).

CASE STUDY

The case study is an aluminum alloy FSAE brake caliper redesigned to be produced by Selective Laser Melting (SLM) process. The DfAM is based Ti6Al4V titanium alloy material replacement to improve high temperatures component behavior and topology optimization to achieve weight saving despite the density increase Fig 3a depicts the optimized brake caliper CAD model. The case study underwent the design phase and product optimization provided about 10% hot deformation and 25% mass reduction.

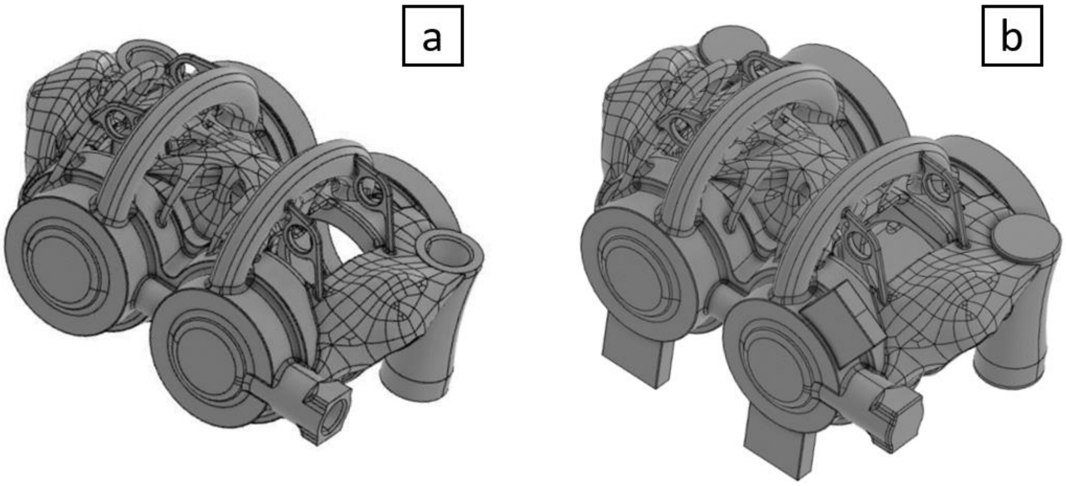


Figure 33: Brake caliper cad model (a) and crude part cad model (b)

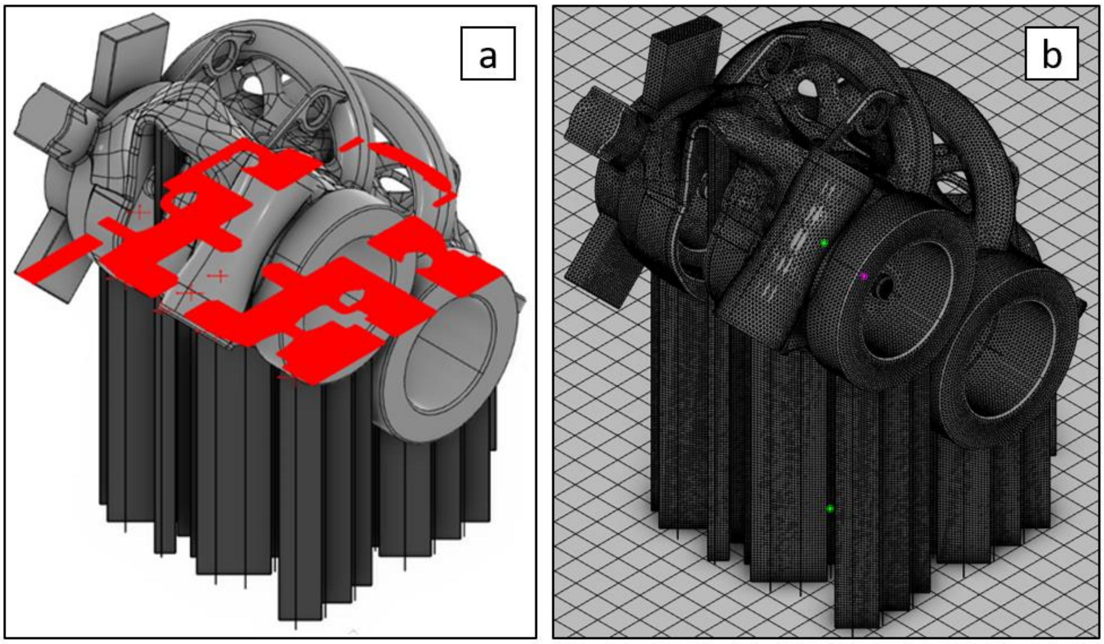


Figure 34: Slicing and scan path (a) and finite element model (b) of build initial setup

This work focuses on the industrialization phase by applying the proposed process design method to prepare component fabrication by a SLM 280 HL machine. Project aims are to provide a reliable build job layout and to achieve the design's requirements. To do that, targets of residual stress containment and deformations containment, as well as feasibility constraints for process and post-process operations (e.g. supports removal), can be defined.

The industrialization process is therefore composed by Coarse Modelling, Build Preparation, and Process Simulation, to return the Initial Setup definition. Coarse modelling is related to functional analysis and process and post-process planning. Fig. 33b depicts the CAD crude model. Appropriate oversize on functional features that require machining post-processing to achieve functional coupling requirements are created. Specific studs are placed on spots to be drilled, specific additional elements to clamp the workpiece are introduced. Build preparation requires virtual machine (e.g. 280x280x365 mm build envelope, scanning system, recoating system, inert gas system, etc.) and tools definition and proper construction and process parameters setting. To generate the layout, a standard slice extension variation minimization strategy is chosen, in order to automatically define a part orientation (X 270° - Y 135° - Z 0°). This strategy smoothens the cross sectional changes along the build direction and therefore it contains residual stress [Mugwagwa 2016]. To generate the supports, standard wired support structures (3 mm spacing) are chosen, with first automatic placement and subsequent manual refinement. The scan path and the slicing of 75 μm are generated following appropriate rules for the titanium alloy processing. slicing The maximum layer thickness value according to machine specifications is chosen to prevent deformation [Zaeh 2010]. Fig. 34 depicts the build Initial Setup.

Selective Laser Melting Process Simulation is then setup, to predict both printing and post-processing operations, by a weakly coupled thermal and mechanical computation. In particular, simulation is based on different steps for the build printing process, subsequent annealing, build-plate removal finally supports removal. A finite element model is created introducing 250k nodes constraint to contain computational cost. Geometric discretization is made of 0.7 mm tetrahedral mesh for the part, 0.5 mm surface mesh for the supports, 5x5x8 mm hexahedral mesh for the build-plate.

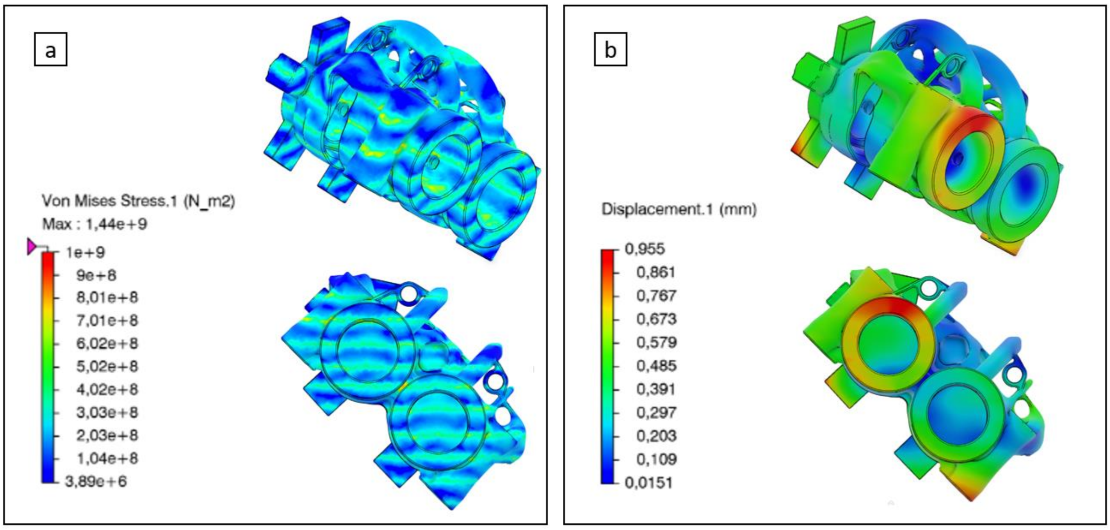


Figure 35: Residual stress map (a) and displacement map (b) returned by initial build setup

Characterized Ti6Al4V material is assigned, elements connections between plate supports and the part are created. Process information for moving heat source and material deposition for mesh element activation are retrieved from the Build preparation programming step. Simulation proper parameters are set in particular for thermal case (e.g. operating temperatures, inert gas flow, heat transfer modes). The annealing step provides a 11-hours thermal treatment based on a temperature ramp. Starting from a 298.15 K reference temperature, a smoothen cycle at 894 K between 10000 s and 30000 s is introduced. Build-plate removal and supports removal are based on proper constraint switches and element mesh elimination. Specific time steps are introduced for time discretization of thermal and mechanical cases. After numerical simulation, different results can be evaluated. In particular, it is relevant to monitor process-induced residual stress after the build phase, residual stress release after post-processing, final component displacement after post-processing.

Fig. 35 depicts the Initial Setup results of the residual stress map and displacement map after the process and post-process numerical simulation. 1440 MPa maximum stress (Max. stress) and 0.955 mm maximum displacement (Max. displ.) can be recognized on local spots. Hereafter, few studies based on Coarse Modelling and Build Preparation subphases are performed in the integrated environment, with the aim to improve the process design by reducing Max stress and Max displacement.

RESULTS

This chapter provides the method application by two Build Preparation optimization studies and a Modelling optimization study. The studies are based on core operations of the aforementioned subphases, exploiting potentials provided from the CAD platform environment. Investigated elements run across the AM industrialization workflow steps. Each process design variant is created starting from the Initial Setup and then simulated. Results are provided and compared to the Initial Setup (see Tab. 1).

Table 10. Maximum displacement and maximum von mises stress of initial setup, orientation study, supports study and model distortion compensation study.

	Initial Setup	**O1**	**O2**	**O3**	**S1**	**S2**	**S3**	**M1**
Max Displ.	0.955 [mm]	+61%	+22%	+53%	+2%	+38%	-14%	-67%
Max Stress	1440 [MPa]	-23%	-8%	-12%	-34%	-1%	-33%	+14%

Build Preparation optimization study

The study aims to apply the Build Preparation optimization loop of the design method. Parts orientation and support generation are chosen steps for evaluation, since they represent critical steps of Build Preparation tasks. Each build job variant is created, the simulation is updated and computation is launched.

Orientation study

Parts orientation represents one of the most influential steps for residual stress and parts distortions. It defines overhanging features and shape and dimension of processed layers. In this study, three different orientation strategies computed by embedded optimization algorithms are investigated. Fig. 36 depicts O1, O2, and O3 layouts involved.

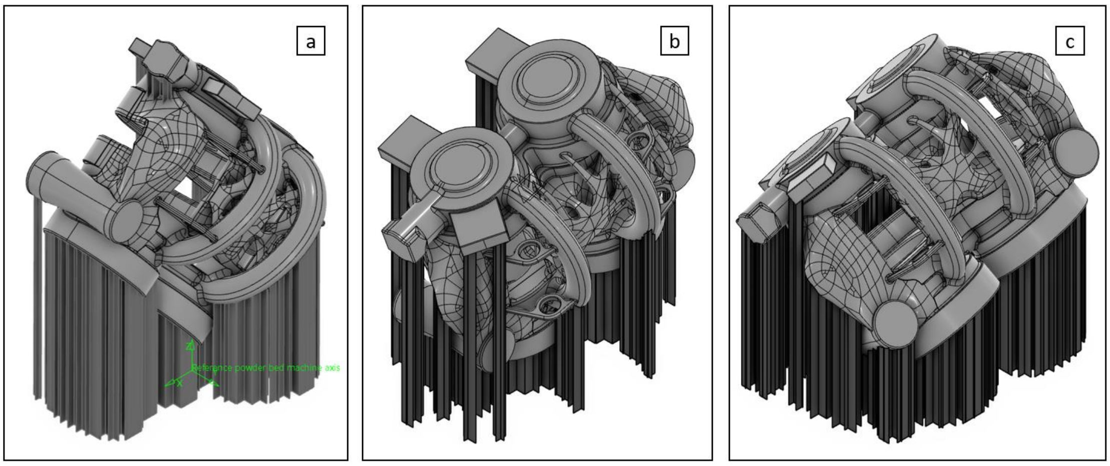


Figure 36: O1 (a), O2 (b) and O3 (c) orientation study layouts

- O1 is based on a slice extension variation minimization strategy with computed 4.77% percentage value. The algorithm returns the X 150° - Y 120° - Z 0° orientation.

- O2 is based on minimization of model area requiring supports strategy (0.55mm2). The algorithm returns the X 0° - Y 200° - Z 0° orientation.

- O3 is run combining both previous strategies with computed values. The algorithm returns the X 318° - Y 198° - Z 0 orientation.

Results of the study are reported in Tab.1. They plain show that O1 and O2 have opposite effects. O1 increases deformations while containing residual stress, whereas O2 leads to less deformation but higher residual stress. O3 is a compromise, providing intermediate results.

Supports study

Supports are one of the most important features of a metal build job, since they have a prominent role both on parts constraints and thermal management in terms of heat dissipation. In this study, the most commonly used supports types are tested and three different supports configurations are compared. The configurations are generated by automatic placement and subsequent manual refinement. Fig. 37 reports a comparison between S1, S2, S3 support structures, and the Initial Setup layout.

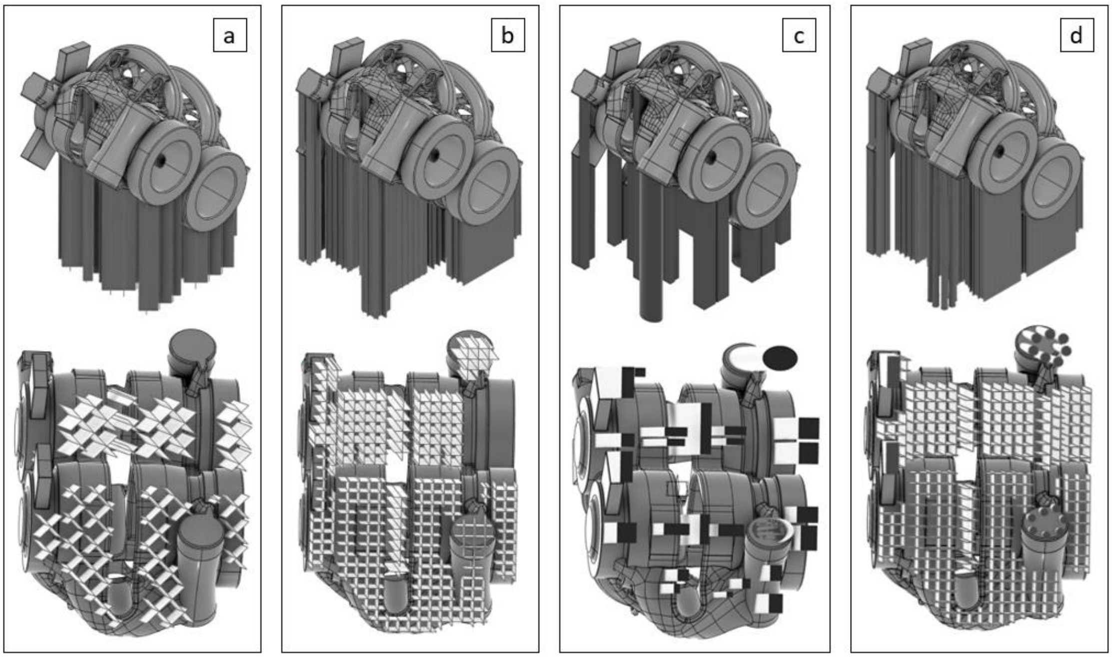


Figure 37: Initial (a), S1 (b), S2 (c) and S3 (d) supports study layouts

- S1 is based on wired (line) support structures with 1 mm spacing.
- S2 is based on volume (block) support structures.
- S3 provides a combination of main support type, such as volume, wired and cones.

A configuration based just on solid supports such as trees or cones has not been tested due to feasibility reasons. Results are reported in Tab. 1. S2 evidently provides the worst results, S1 returns a quite low deformation with the evident benefit of residual stress reduction, S3 is clearly the best configuration, providing concurrent residual stress and deformations reduction.

Modelling optimization study

Many strategies of parts shape (geometry) modification in CAD environment can be involved by applying the Modelling optimization loop, having an impact on process-induced residual stress and distortions. In this case, a method to compensate distortions is studied.

Model distortion compensation study

The study aims to reduce parts distortions by generating a CAD model that negatively compensates the geometry with predicted build distortions. Then, the model in the build job is being replaced with the negatively compensated geometry, the process should return reduced displacement results.

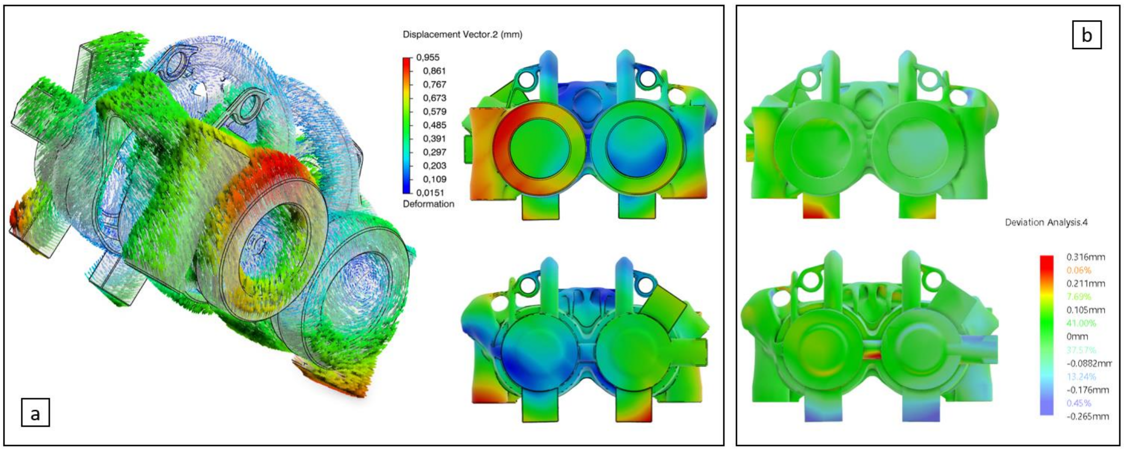


Figure 38: Modelling optimization study nodal displacement field (a) and displacement map results (b)

M1 represents the Model distortion compensation study. Working on Initial Setup build job results, the computed nodal displacement vector field is exported. Fig. 38a depicts the nodal displacement applied to the model. Subsequently, the vector field is applied to the geometry, in the analogue way to create the deformed shape but introducing a -1 coefficient in order to create the pre-deformed one. The pre-deformed model is replaced, the build job and simulation are updated and the computation is launched again. The result after the modelling optimization loop is then used as before to create the deformed geometry, which undergoes a deviation analysis. Fig. 38b depicts the results of the deviation analysis performed between the deformed geometry (after the loop) and the initial model.

Results of the M1 study are reported in Tab. 1. The Modelling Optimization study provides an impressive result on deformation results, which are reduced by about 67%. In particular, the maximum shape deviation compared to the original model is 0.316 mm. Nevertheless, the drawback is about 14% residual stress increase.

Preliminary discussion

The three studies provided very different results in terms of residual stress and parts distortions. Table 10 collects the results in terms of percentage variation compared to the Initial Setup.

By analyzing post-process results, we foresight a very interesting approach to set up the final industrialized job. Both orientation study and supports study return good results, in particular, providing some configurations with high residual stress reduction. Thus the best configurations can be combined to define a final layout that should guarantee a low residual stress amount. Hence, the final layout can be simulated and a modelling optimization loop based on model distortion compensation can be performed to highly reduce part distortions. Therefore, by applying the process design method combining firstly a Build Preparation optimization loop and secondly a Modelling Optimization loop we should be able to define an industrialized build job providing concurrent containment of residual stress and parts distortions.

The results will be finally discussed in chapter 5

4.4 Simulation driven integrated approach

As aforementioned, DfAM requires that the effects of design on manufacturing and vice-versa must be taken into account to optimize product performance and quality minimizing development and production time and costs. Therefore, the methods to be developed are focused on Product Optimization and Process Optimization, to be performed respectively through the Design phase and the Industrialization phase.

Previous chapters provided the study of the elements that are going to be synthesized in integrated product and process design approaches. Chapter 4.1 provided the assessment of CAD platforms as backbone tools to develop computer-based DfAM approaches. Chapter 4.2 proposed different approaches to optimize the product by exploiting such tools and the systematic integration of topology optimization in DfAM workflows. Moreover, a detailed case study developed through one of these approaches to demonstrate its effectiveness and suitability was reported in chapter 4.2.2. Chapter xx proposed a design method to optimize the process based on the use of process simulation. Moreover, chapter 4.3 it presented the required studies to develop the simulation and evaluate qualitative and quantitative results. Finally, a detailed case study developed through the process optimization approach was reported in chapter 4.3.3 to demonstrate its effectiveness and suitability for AM industrialization.

Two Computer-based and simulation-driven DfAM methodologies, related to the two main metal AM processes, are being performed, to achieve concurrent high-performance design and reliable production of metal components. Therefore, the two applications concern:

- L-PBF integrated optimization
- L-DED integrated optimization (further development)

The first study represents an application of the product and process integrated optimization for components to be produced by PBF process. The second is related to further development which is in progress to provide an analog integrated approach to optimize components to be produced by DED process. These works represent complete case studies of product and process design that are synthetically reported since each phase has been already presented and supported by case studies in previous chapters.

4.4.1 L-PBF integrated optimization

Case study is from a powertrain, in particular an internal combustion engine (ICE) piston of a racing motorcycle. The aim is to test engine additive manufactured components such as the engine piston, exploiting TO to reduce mass, since engine inertial loads have to be minimized. Literature provides some interesting piston design approaches based on Topology Optimization. Du et al. [Du 2011] first investigated structural behaviour, Zhao et al [Zhao 2014] and, more recently, Gaidur et al. [Gaidur 2020] introduced also thermal considerations. Barbieri et al. first combined TO and AM for a steel piston redesign application [Barbieri 2018]. Lately, Mahle and Porsche demonstrated even industrial feasibility and endurance capability of such innovative solutions [Abele 2021]. Re-design of the engine piston achieves structural targets of 29g mass saving with 15% mean stress reduction and 10% safety factor improvement. Industrialization based on process simulation provides a final build job to carry out a reliable SLM manufacturing process. The holistic approach steps for product-process design are now synthesized.

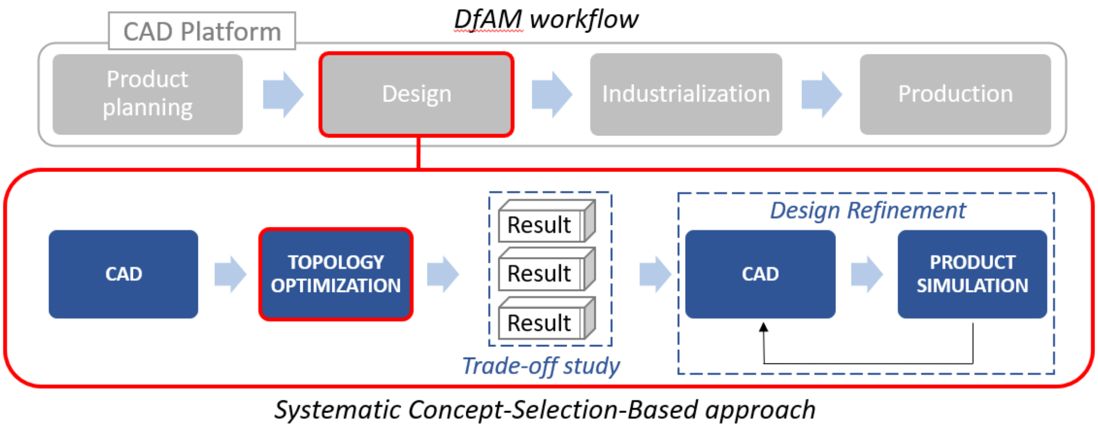


Figure 39: Systematic Concept Selection-based Approach for Product Optimization.

Product optimization has been achieved through the Systematic Concept-Selection-based approach. A conceptual solution exploration step is performed through TO by generating sundry concept results. Subsequently, they can be evaluated to drive design variants selection with respect to design requirements (KPIs) through a Trade-off study, which represents significant support for the designer. These driven solution generation steps become simple in CAD-based environments integrating TO and Product Simulation (ProdSIM) and supporting automatic geometry construction features. Afterward, just one manual final redesign is required for design interpretation. A final Design Refinement step based on ProdSIM and CAD can be performed to further improve model performance. In this way, a double-level optimization through an integrated environment is made possible: the first involves design automation to drive the Trade-off study step, and the second requires manual design interpretation to improve the concept solution by the Design Refinement step. The final model is the output of the design phase, which is ready for industrialization.

Figure 40 shows the structural behavior of the original part with respect to the main loadcases, that are Top Dead Centre during Combustion (TDCC) and Top Dead Centre during Intake TDCI).

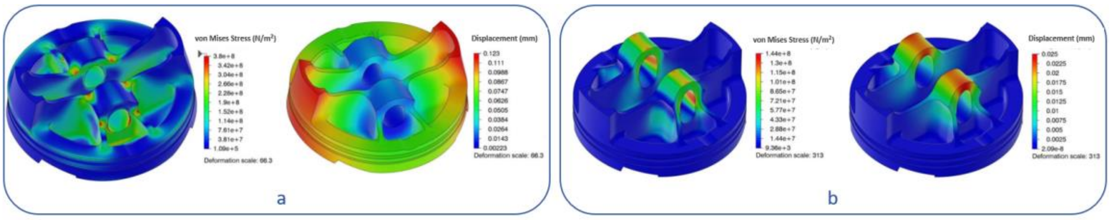


Figure 40: Original piston structural behavior in TDCC (a) and TDCI (b).

Figure 41 shows the design variants involved in Trade-off study to perform the Concept Selection step.

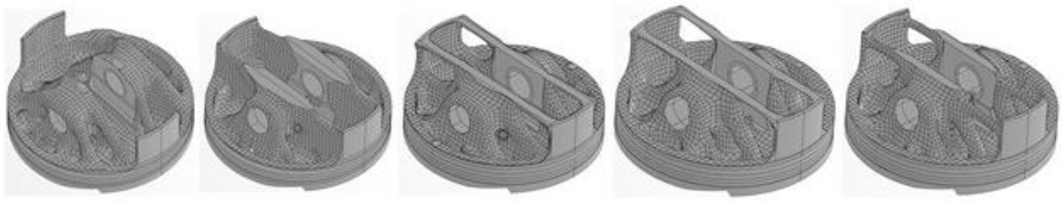


Figure 41: Topology optimization design variants for Concept Selection.

Figure 42 depicts the stress distribution map in TDCC and TDCI of the topology optimized model presenting the highest score in the Trade-off study considering structural KPIs.

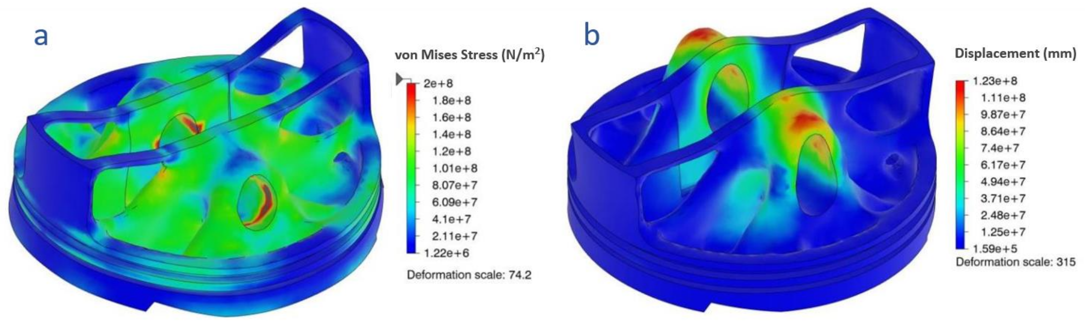


Figure 42: Stress distribution fields of selected concept in TDCC (a), TDCI, (b).

Considering the Design Refinement step, the detailed CAD modelling involving design interpretation is depicted in figure 43.

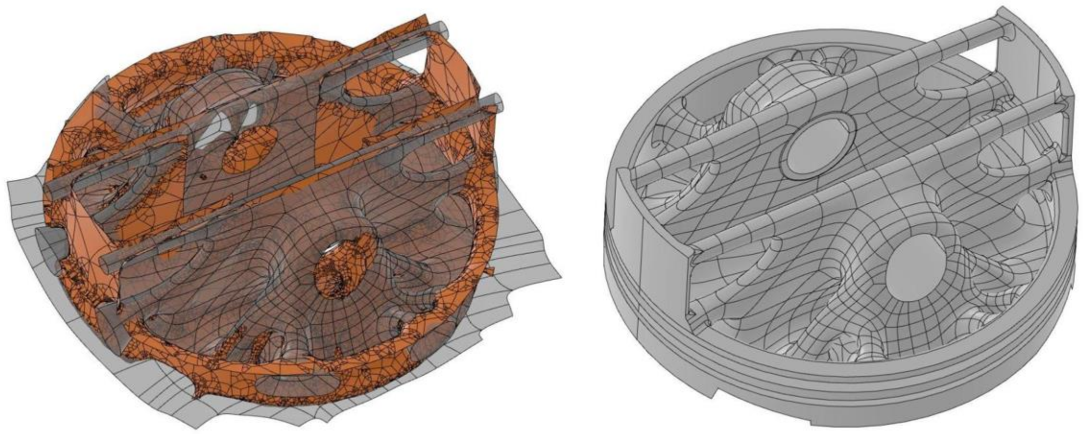


Figure 43: On the left, design interpretation process through freeform surface modelling; On the right, topology optimized piston final design after Design Refinement.

The Design Refinement aiming to improve the optimized component behavior, which is based on just one manual re-design returns the model whose results (TDCC, TDCI) are depicted in Fig. 44.

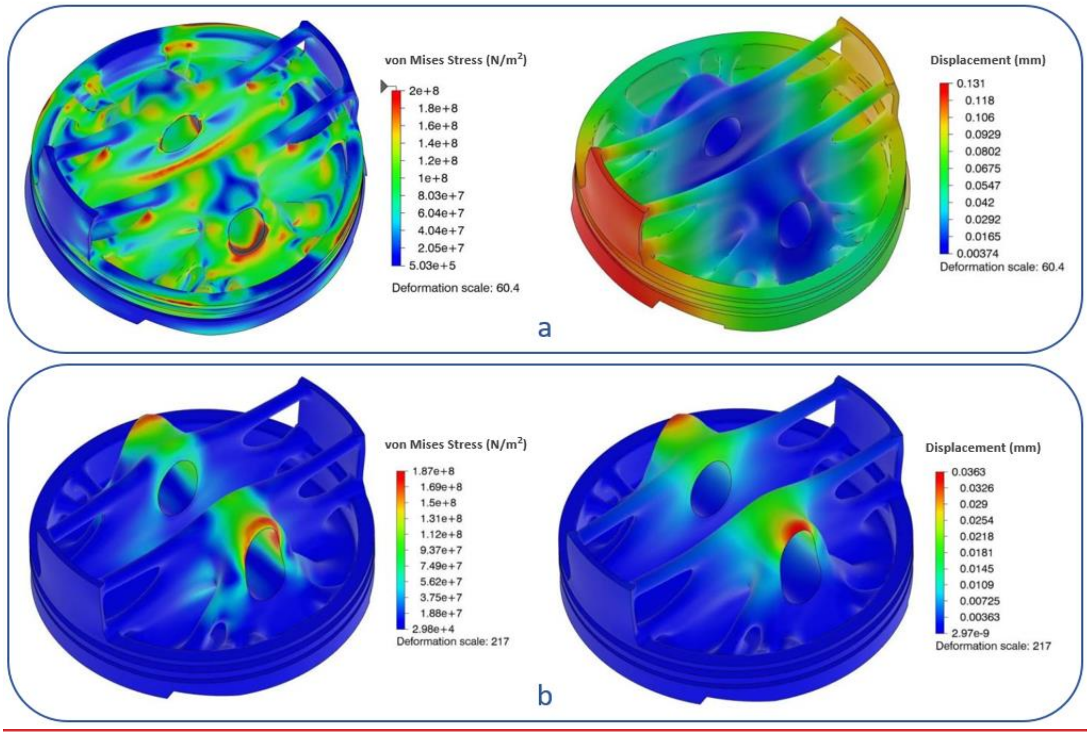


Figure 44: Topology optimized piston structural behavior in TDCC (a) and TDCI (b).

The redesign provided interesting results. The product analyses show an appropriate stress reduction, with a safety factor equal to or higher than the original component and displacement, and almost the same displacement. Regarding the main objective or rather mass saving, after the final optimization loop, the Design Refinement step produced a component with an impressive weight of 109g. Mass saving is therefore more than 20% compared to the original component. Anyhow, on the side of method and application, a remark is that the systematic approach structure allows integrating additional product or process studies (e.g. buckling, fatigue life, thermal, industrialization, printing, etc.) into the design phase.

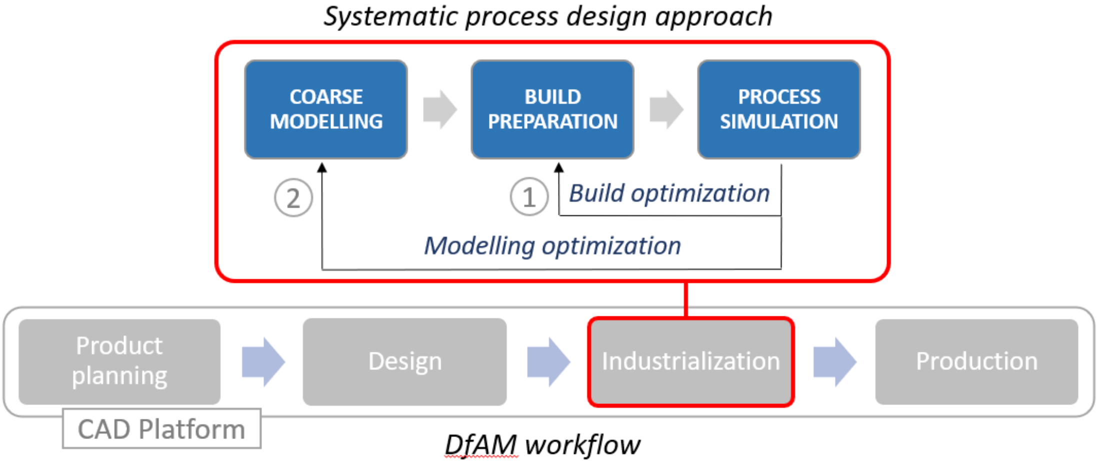


Figure 45: Systematic Process Design Approach for Process Optimization.

The process optimization has been achieved through the Systematic process design approach.

The approach is based on the use of process simulation results to drive the coarse modelling and the build preparation industrialization subphases. Firstly, the crude model is created and introduced in the virtual machine environment, where the initial build job is prepared. The task involves the orientation study and the supports study to return a proper layout. Secondly, a process simulation is run, and the results are used for the build optimization step, to improve the initial layout with the aim to reduce the residual stress. Afterward, a second process simulation is run, and the results are used for the modelling optimization step, to reduce the component deformations induced by the process. This operation becomes possible through the model distortion compensation step. The combination of the build optimization and the modelling optimization steps allows to concurrently contain components' residual stress and deformation. To conclude, the final build job is the output of the industrialization phase, the machine code can be generated, and the production can start.

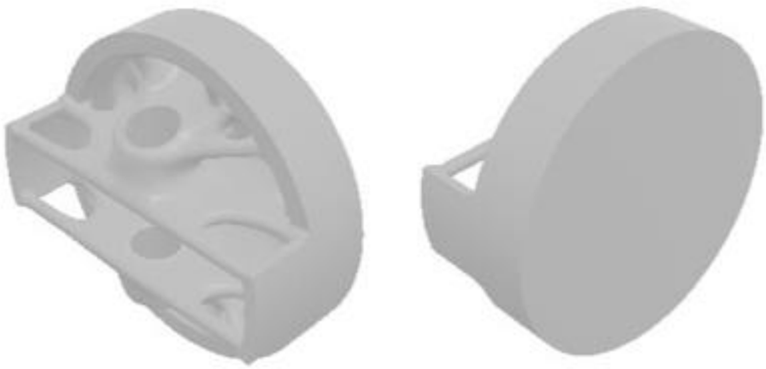


Figure 46: Engine piston crude part cad model (b)

Figure 46 depict the crude cad model developed in the Coarse modelling phase, considering the process and post-processing operations.

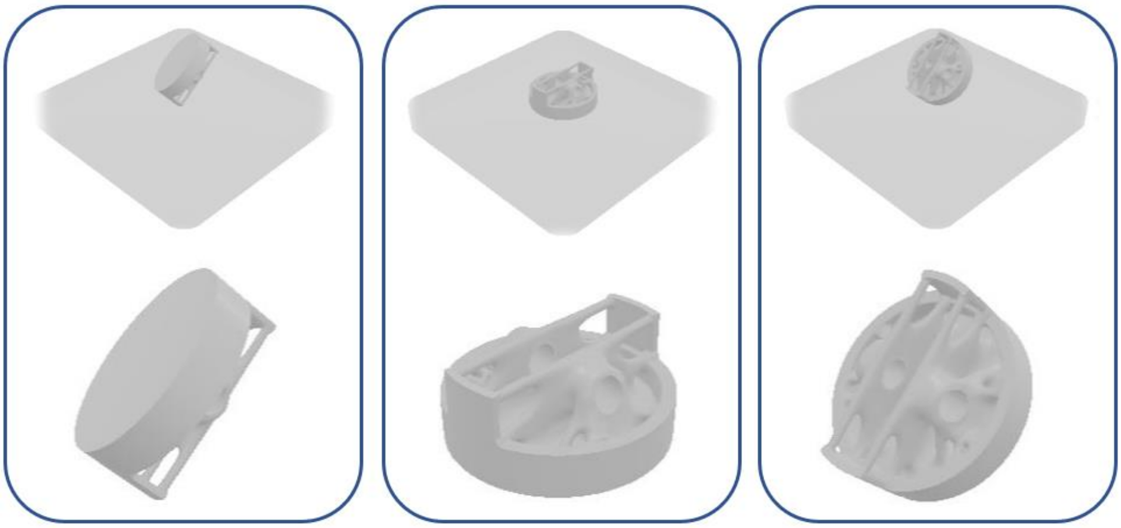


Figure 47: Engine piston orientation study layouts

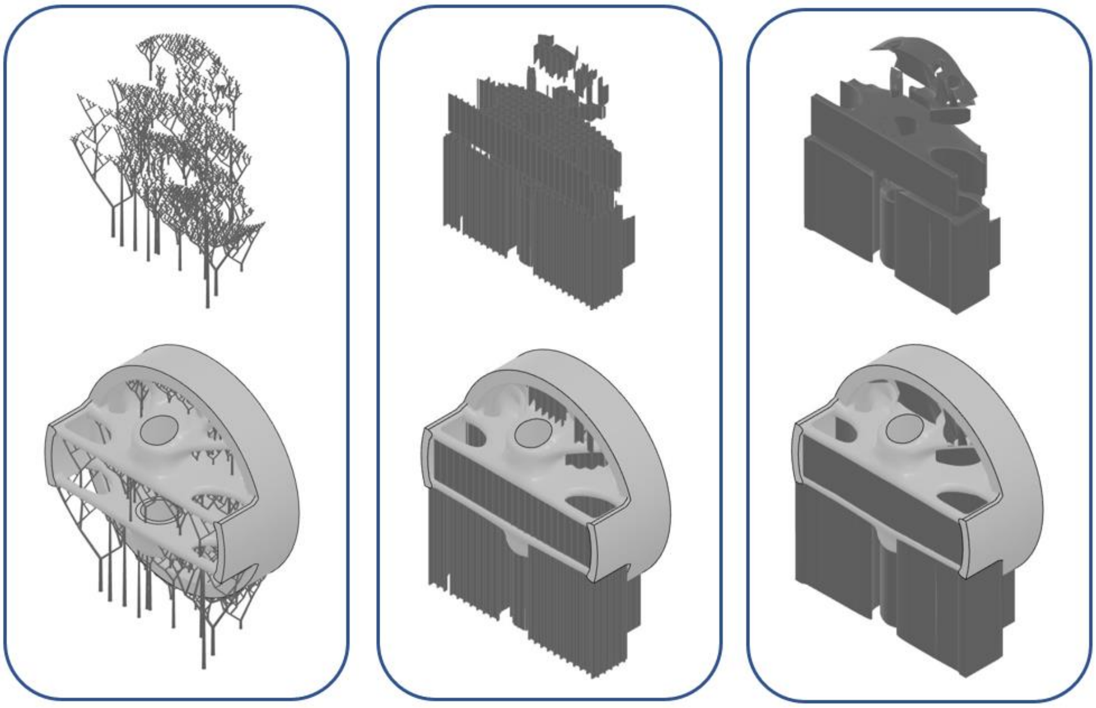


Figure 48: Engine piston supports study layouts

Figures 47 and 48 respectively depict the studies on the orientation and the supports involved in the build preparation task. Whereas figure 49 reports the scanning path generation used to set the process simulation task.

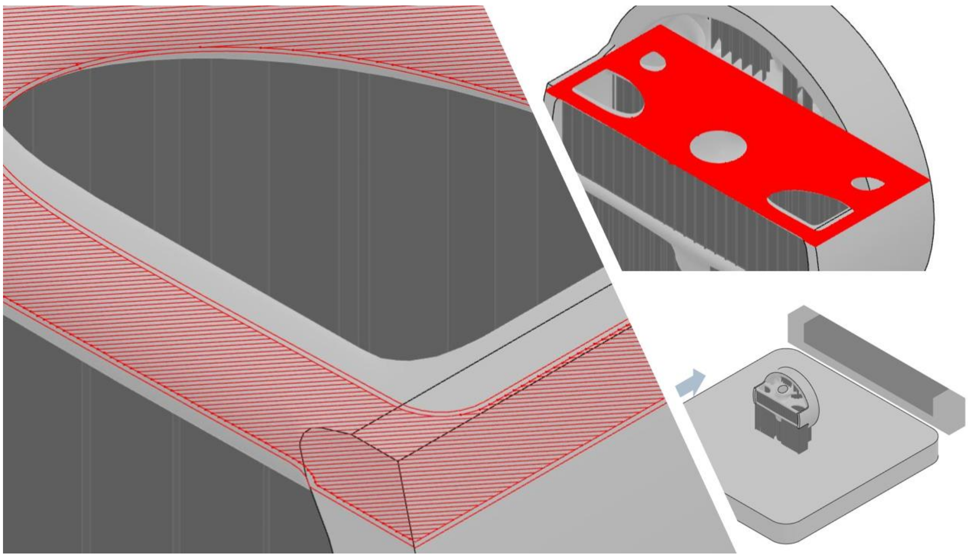


Figure 49: The engine piston build preparation and the slicing and scanning path generation.

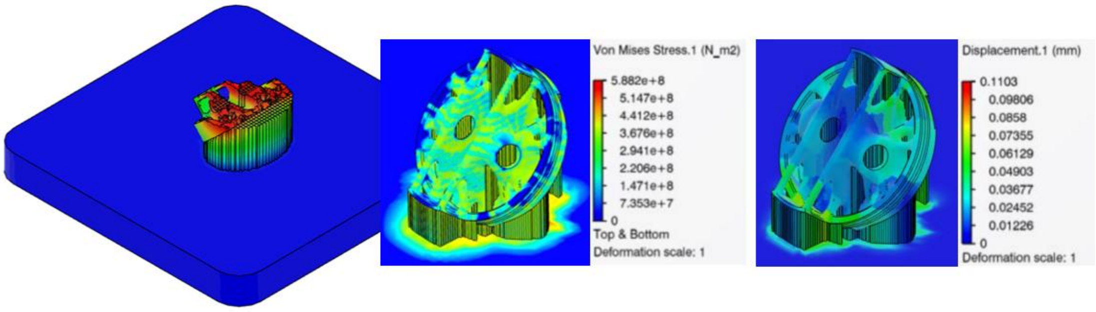


Figure 50: The engine piston manufacturing process behavior

Figure 50: returns the results from the process optimization approach to predict the behavior of the SLM production phase.

A synthesis of the Simulation Driven Integrated Approach for DfAM has been provided to confirm the method's suitability for the design industrialization of metal additively manufactured components. The case is reported to retrace the steps of product optimization and process optimization respectively achieved through the Concept-Selection-based systematic approach and the process optimization systematic approach, which were deepened in previous chapters. The case study results confirm the efficient achievement of concurrent optimal product requirements and expected process reliability. From the application, we can infer that the approach that integrates simulations to drive the product and process design by making use of CAD platforms is suitable to effectively support the Design for Additive Manufacturing in industrial applications.

The results related to the integrated product and process design example will be discussed in chapter 5.

4.4.2 L-DED integrated optimization (further development)

Even for the case of development of components to be produced by DED, the definition of specific approaches to optimize both the product and the process are needed. Especially concerning DED systems, firstly the connection between design and manufacturing is significant, secondly the academic and industrial examples are fewer compared to other metal AM technologies. A promising application is the Remanufacturing of existing components to produce design variants integrating functional design. This work concerns the study of a laser-based Direct Metal Deposition process. Computer-based simulations such as topology optimization, product simulation, NC code preparation, and process simulation are considered the key steps to structure a Design for Additive Remanufacturing (DfAReM) workflow. Figure 51 depicts a framework for the DfAReM approach. The aim is to apply such integrated approaches to the design of high-performance components to be produced by the Directed Energy Deposition process. For this purpose, there is need of specific DfAM approaches to understand exactly the location and the amount of the deposited material, defining the shape of the structures, and the strategies to build them.

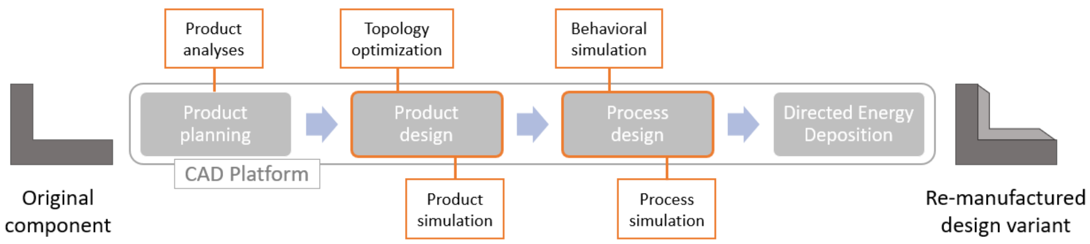


Figure 51: A framework for DfAReM based on CAD platforms

The case study is from a suspension system, in particular a wishbone of a normal production car. The project's aim is to generate a high-performance design variant by optimizing the material deposition to increase the structural behavior. The redesign objective becomes to reduce stress concentration on the two identified critical areas with a specific constraint of material deposition. Tests on the deposition process, the materials, machine programming, kinematic process simulation, and thermo-mechanical process simulation have been performed in a CAD-based integrated environment. Currently, process feasibility is being evaluated through simulation and experimentation. The re-design based on product and process simulation driven optimization will be also enriched by additional simulations (Computer-Aided Tolerancing (CAT) and Computer-Aided Cost Estimation (CACE)), and physical production and testing.

5 Discussion

5.1 Assessment of CAD-platform-based approaches

At the state of the art, the Design for Additive Manufacturing workflow to produce topology optimized parts consists of different phases that must be performed using different CAD, CAE, and CAM specific software. This leads to adopting many interchange files in the sequence of operations and in the required iterations. Two kinds of issues have been recognized, the first at the local level, concerning the operations of each phase, and the second at the global level, regarding the entire workflow.

The management of the Design for Additive Manufacturing workflow can be solved with a holistic approach, through the use of computer-aided integrated tools. CAD platforms might represent an effective choice to overcome these issues with the aim of shortening product development time and optimizing product and process performance. The CAD platform considered is commercial software so that it is both available on the market and accessible by users and companies for DfAM implementation. The benchmarked tool is the Dassault Systèmes 3DExperience, which is a configurable CAD platform to support the design process by combining modelling, simulation, and data management through the possible integration of CAD, CAE, CAM, and PLM tools. Indeed, it represents one of the software from the state-of-art suitable for DfAM implementation.

Global level

Since CAD platforms are based on integrated product-process applications, they let to simplify and reduce data management and exchange. In order to assess the effectiveness of CAD platforms at the global level, an automotive case study to be produced by laser Powder Bed Fusion has been developed along with the *Design* and *Industrialization* phases.

At the global level, it emerged that every re-design step is simplified by the parametricity and associativity between all the applications. The use of STL files could not be required anymore as interchange elements, as modeling support, for re-design, and for build preparation. Also, there are some potentials introduced at the local level. Geometry reconstruction and part design can be simplified by solid models as output from topology optimization. Industrialization can avoid dealing with meshes and related fixing operations, designed supports can be easily introduced, and part re-design can be very quick. It is possible to perform only one file exportation of the final industrialized job, at the end of the workflow, for parts production. Possible troubles in data management can be minimized, it is possible to shorten the entire product development workflow, and the lead time of design and industrialization operations can be reduced.

Local level

It has been remarked that the use of integrated CAD platforms can improve the method's effectiveness speeding up the workflow at the global level, but a local level evaluation on specific tasks was required as well. Working on an automotive case study to be produced by laser Powder Bed Fusion, the effectiveness of the integrated tools is evaluated, and the results are compared to those specific for each phase of the workflow, that are taken as reference.

At the local level, results show the possibility to replay the core steps that compose the workflow and can be performed at the state of art, eventually either avoiding a few specific features or revising the adopted solution. This is due to the differences between the implemented tools. Results are in some cases exactly analog, otherwise, they can be believed anyway acceptable. The advantage offered by the integrated tools is to connect the environments, not only for file interchange and data manipulation but also for linking the features between the applications, keeping the information with the associativity. This is valid not only for re-design operations initially investigated but also for simulations, keeping settings, and recovering and exploiting their results. To conclude, there is no advantage in replacing a stand-alone tool with an application of an integrated platform, rather than implementing the whole method and the workflow into a platform. Alternatively, adopting the platform for just one between design and industrialization optimization could be a benefit.

5.2 Systematic integration of Topology Optimization

The framework of current capabilities in Design for Additive Manufacturing of topology optimized components, concerning an analysis of state-of-art methods and tools, has been described. Starting from general approaches, it has been shown that it is possible to create advanced solutions based on systematic approaches. Moreover, it emerged that they can firstly benefit from the exploration of conceptual solutions, which actually represent one of the biggest obstacles for DfAM since the critical point is to properly exploit the potentials. Secondly, processes can gain speed, flow, and effectiveness concerning product development lead time reduction. Nevertheless, the development of the most advanced methodologies presented is actually tied to tools. It has been shown that most processes can benefit from integrated tools such as CAD platforms. Efforts have to be spent on the creation of systems in order to provide “ready to print” models. In addition, the development of generative design features could currently represent an optimal solution, while introducing also multi-objective optimizations that lead to obtaining the optimized product and process at the same time. Some researchers are moving toward this direction, but actually, improvements have to be concurrently carried out on design tools and proper design approaches. Actual means should be improved with the aim of adding features and connecting the workflow steps in order to facilitate DfAM on both product optimization and process optimization.

5.3 Product design based on TO

To implement the DfAM through a systematic approach based on topology optimization and validate it in a real case, an entire design optimization of an automotive component to be produced by laser Powder Bed Fusion (PBF) process has been performed. In the application of such a complex component, the DfAM consists of a material replacement to better resist high temperatures and a topology optimized shape to achieve weight reduction despite the material density increase. Structural and thermal behavior has been discussed. DfAM process-specific techniques have been implemented for internal geometrical features and optimized shapes. The Systematical Design Methodology –based approach for DfAM has been presented and finally, the workflow based on a CAD platform has been synthesized. The approach is based on a structured iterative design refinement; Loops for product optimization, each of them performed in the integrated CAD platform, can be outlined at different levels. The first loop includes Topology Optimization, automatic geometry construction, and Product Simulation and produces conceptual solutions. Automatic tools for design interpretation are used and loops are made fast thanks to the integrated platform. The second loop includes CAD and Product Simulation and lets the development firstly of embodiment solutions and finally definitive ones, adding elements of the detail design. A CAD step that requires manual geometry interpretation, which is a high time-consuming operation, is therefore required just for the first iteration. Conversely, subsequent re-design loops that are needed to refine the design result are extremely facilitated by the integrated environment.

5.4 Process simulation qualitative and quantitative validation

Design for Additive Manufacturing approaches aim at concurrent optimization of products and processes. Efforts have to be spent on the industrialization phase to achieve “print right first time” build jobs. Process simulation can be used to overcome components' shape defects by reducing process-induced residual stress and distortions. Therefore, the Selective Laser Melting thermo-mechanical process simulation has been implemented in a CAD platform based approach. This element resulted fundamental in order to perform the optimization starting from predicted results and acting both on models' re-designs and build preparation tasks. Two case studies have been developed, the first to perform a qualitative validation of the simulation approach, and the second to achieve a quantitative validation of predicted results compared to experimental data. To achieve effective suitability for practical applications, the finite element simulation includes not only the printing process but also the required post-processing operations (i.e. cooling, heat treatments, parts removal, supports removal). Results confirm simulation feasibility and expected support for the method as well as a discrete level of accuracy for both process and post-processing phases. Indeed, studies can be carried out on identifying the optimal balance between results accuracy and computational cost.

5.5 Process design based on simulation

A design method based on integrated process design supported by process simulation to improve the metal AM industrialization phase has been presented. The aim is to optimize the process design by reducing process-induced flaws in final components such as residual stress and distortions. The case study is an automotive component to be produced by laser Powder Bed Fusion Process. The study concerns the application of the described CAD-platform-based process optimization on a complex component. In particular, it emerges that a two-stages approach composed of a first Build Preparation optimization loop and a subsequent Modelling optimization loop could lead to the definition of a reliable build job providing a concurrent reduction of residual stress and distortions. Subsequent studies are to overcome the challenge of the need for holistic approaches by performing simultaneous integrated product and process Design for Additive Manufacturing. A remark is that the presented process optimization workflow can lead to improvement of the quality of printed components by involving manual operations. The designer actually has to interpret simulation results to define the operations to be performed on the part model and the 3D printing job. Further developments could lead to operations linkage so that optimization process phases can be automatized

5.6 Simulation driven integrated approach

Once each step of the proposed computer-based methodology for DfAM has been specifically validated, the systematic approach for concurrent product optimization and process optimization that has been presented is applied to a challenging automotive component to be produced by laser Powder Bed Fusion. For product design, The redesign is performed through the Concepts selection –based approach for DfAM. Its effectiveness is related to the exploitation of benefits provided by integrated CAD platforms, using a double-level optimization approach, and combining automation and manual design. Integration of advanced tools for design exploration, product validation, and design variants selection can be used to drive the design process steps to obtain high-performance components design. Moreover, flexible integration of additional product simulations can be performed as well as KPIs for the concept selection step can be adapted to meet different design requirements. The case study redesign produced optimal results in terms of mass saving and structural performance. For process design, the simulation driven process optimization has been performed. By evaluating different configurations for build preparations and exploiting the integrated simulation to predict the manufacturing behavior, the industrialization phase achieved optimal results in terms of residual stress and distortions, to return a build job for reliable production.

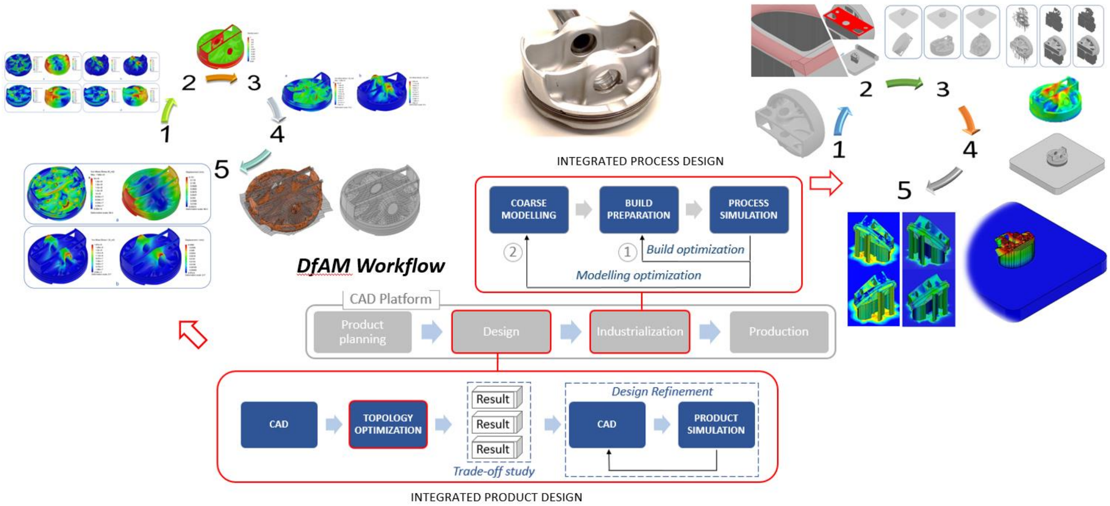


Figure 1: The Simulation Driven Integrated Approach applied to the redesign of an optimized engine piston to be produced by L-PBF process.

5.7 Conclusions

Concerning CAD platforms' global level evaluation, it emerged that every re-design step is simplified by the parametricity and associativity between all the environments. The use of STL files could not be required anymore as interchange elements, as modeling support, for re-design, and for printing preparation. It has been shown how a holistic design approach implemented through CAD platforms, can speed up the entire workflow. Concerning CAD platforms' local level evaluation, results show the possibility to replay the core steps that compose the general DfAM workflow and are performed at the state of the art, eventually revising the solution by adopting proper approaches. The advantage offered by the integrated tools is to connect the environments, not only for file interchange and data manipulation but also for linking the features between the applications, keeping the information with the associativity. This is valid not only for re-design operations but also for simulations, keeping settings, and recovering and exploiting their results.

Product design: the “ready to print” challenge

Considering the proposed advanced approaches based on systematic integration of Topology Optimization, it emerged that firstly they can benefit from the exploration of conceptual solutions to exploit AM potentials, which actually represents one of the biggest obstacles for DfAM. Their effectiveness is related to benefits provided by integrated CAD platforms for product-process design, combining automation and manual design to simplify and minimize the number of re-design loops. Integration of advanced tools for product validation and design variants selection can be used to drive the design process. Moreover, flexible integration of additional product or process studies (e.g. buckling, fatigue life, thermal, industrialization, printing, etc.) into the design phase can be performed to meet different design requirements. For example, a double-level optimization approach based on systematic generation and selection of design variants, that combines automation and manual design, and integration of different simulations, can provide optimal design results. Thus, processes can gain speed, flow, and effectiveness concerning design requirements and product development lead time reduction.

Process design: the "print right first time" challenge

Concerning Powder bed Fusion process optimization related to DfAM, the thermo-mechanical process simulation resulted fundamental in order to develop the methodology to perform the optimization starting from predicted results and acting both on models re-designs and build preparation tasks. Results confirm simulation feasibility and expected support for the method as well as a discrete level of accuracy for both process and post-processing phases. Data related to systems, products, and processes can be linked together and retrieved for all steps, and thus, starting from process simulation results, we can drive process design. Considering the aim to optimize the process design by reducing process-induced flaws on final components such as residual stress and distortions, it emerges that a two-stages approach composed of a first Build Preparation optimization loop and a subsequent Modelling optimization loop could lead to the definition of a reliable build job providing a concurrent reduction of residual stress and distortions.

The final result is a Computer-based and Simulation-driven integrated DfAM methodology to be achieved through the combination of the studies (Figure 1). It allows to obtain efficiently both optimal product requirements and expected process reliability. The systematic approach for concurrent product-process optimization based on CAD platforms is therefore suitable to effectively support the Design for Additive Manufacturing of industrial applications. Table 1 resumes the features implemented in the approach with respect to the research gap that emerged from the state of the art.

Table 1: 5.6 Features of the ‘simulation driven integrated approach’

Aspects	Gaps/Challenges	Possible solutions	Implemented features
AM	Vertical research	Horizontal research	Process chain focus, integration
	AM limited industrial spread	Methodologies	DfAM oriented
DfAM	Need of specific knowledge	Methodologies	Systematicity
	Holistic approaches	Methodologies	Product-Process design integration
Product design	Complex and slow design steps relationships	Facilitate and speed up design	Data consistency, associativity, systematicity, integration, automation
	AM potentials exploitation	Design exploration, workflow suitability	Integration, Optimization based on variants generation and systematic selection
Process design	Complex and slow industrialization steps relationships	Facilitate and speed up industrialization	Data consistency, associativity, systematicity, Integration, automation
	Users experience approaches	Methodologies	Systematicity
	Process reliability	Process simulation, workflow suitability	Integration, Optimization based on simulation driven approach
Tools	Tools Capabilities	Advanced features	Data consistency, associativity, automation
	Concurrent tools and methodologies evolution	Methodologies	Systematicity, Integration, CAD-platform-based

Additional studies can be performed to evaluate from an economic point of view the advantages in both the design and industrialization stages related to the use of such integrated methodologies.

On the side of the methodology, further developments could lead to operations linkage so that the optimization process phases can be automatized.

On the side of the application, further developments concern the extension of the methodology from Powder Bed Fusion to other metal additive manufacturing processes. In particular, proper variants of the approach are being applied to the design of high-performance automotive components to be produced by Directed Energy Deposition.

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Chapter 3 -

Chapter 4 -

Chapter 5 -

Appendix

From the points analyzed in Chapter 3, we can understand that DfAM approaches are strictly related to the capabilities of computer-aided design tools [1,2]. Different design tools not only offer different features, but also they may require different approaches, different number of redesigns, impacting the product development time. Thus, an evaluation method for design tools for TO is going to be introduced. It can be used for the tools selection phase for TO based product design or, in a wider perspective, as support for industrial settings embracing AM for CAX platform selection. Hereinafter, we will discuss about TSs referring in general to both sets of standalone design tools and integrated CAD platforms.

1 Method

The evaluation approach is based on the construction and subsequent application of KPIs matrices concerning the features required in order to perform the tasks that compose the design workflow. Their development is based on the study of both the general TO workflow described in Chapter 2 and the currently available design tools. The goal of the approach is the direct relationship between the definition of a general workflow for the design based on TO and the selection and organization of KPIs for the tools assessment. The focus is therefore on the behavior of tools features necessary to implement the method, indulging the designer’s intent. Conversely, the investigation logical path is kept simple and the subsequent data manipulation is well established.

1.1 KPIs matrices adoption

The use of KPIs and integration of objective approaches proposed in previous works related to assessment and selection of software tools [3;4] represents the basis of the suggested assessment approach. KPIs are expressed by the Tasks to be performed to compute a TO, and they are broken down into several matrices. Each matrix was built with the idea of being easily expandable, in order to be able to add as many features as necessary. Furthermore, objectives of clarity and impartiality have been considered during the design of the matrices, and therefore of the method. To fulfil the first, each matrix must be interpreted according to a logical path that goes hand in hand with the TO workflow. As regards impartiality, the impossibility of expressing personal judgement was satisfied by formulating Requests. A Request is a specific action that can be performed to set up a TO. These have been formulated as direct questions so that they must be answered only in a binary way: positive or negative. A Request is satisfied when a specific implemented feature can perform the described action. In this way, the benchmarking is no more dependent on the user experience for the sake of objectivity. Figure 1 depicts the logical path that describes the systematic approach for Request analysis and method application. To avoid flaws in the answer choices, if a request is satisfied only in part, it is possible to indicate the answer "Not completely", indicating the reason or what is missing in the software to completely carry out that Request.

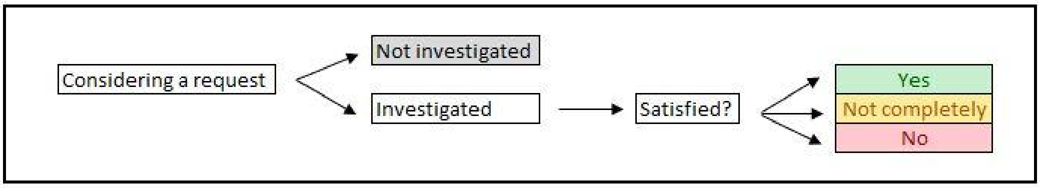


Figure 1. Logical path for Requests investigation.

1.2 KPIs matrices structure

The evaluation approach combines the TO workflow (Chapter 2) and the usability of the selected tool. An overall of 4 evaluation phases are considered:

I. Geometry preparation (GP);

II. Optimization Setting (OS);

III. Result and Post-processing (R&PP);

IV. Interface and user experience (IT).

In general, the method is therefore based on sundry matrices arranged following the phases suggested, whose structure is depicted in Fig. 2 and then described.

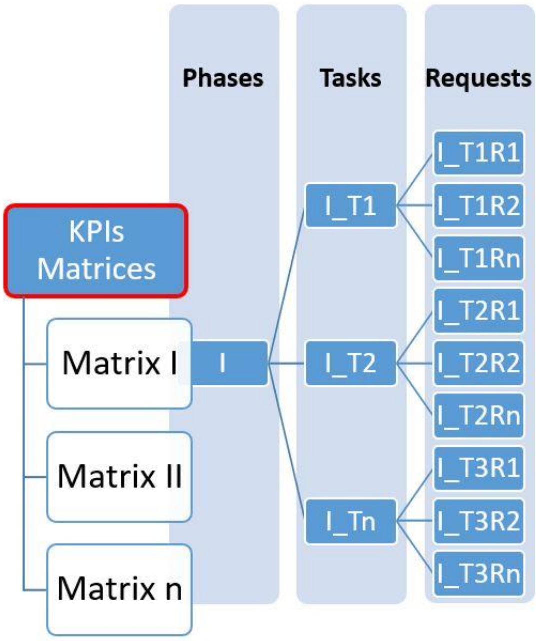


Figure 2. KPIs matrices layout.

Each matrix, representing a Phase (I, II, ..., n) of the workflow, is composed of a series of Tasks (T1, T2, ..., Tn) to be performed. Each Task can be fulfilled through specific Requests (R1, R2, ..., Rn), which represent the object of the evaluation through the described logical path.

In this specific case, the four evaluation Phases represent respectively matrices I (GP), II (OS), III (R&PP), IV (IT). In order to organize the structure of the matrices, each of them has been subdivided with respect to the Tasks that the concerned phase of the optimization involves. A Task is a stage or an aspect of the workflow that is essential to set a computation with reliable results and therefore express a KPI. To complete a Task there are several settings and parameters to be set, different between the TSs, which are the already mentioned Requests. A description can be added for each Request to have further information about the question. Each Request is identified by a reference Code to easily organize them. Table 2 reports an example of the application of a matrix row. Firstly, the request can be investigated within the software, then, if the analysed TS allows the user to import an STL and so the Request is satisfied, a positive answer can be inserted in the status column. In case the Request was not completely satisfied, more details can be added to explain the reason or what is missing.

Table 1. Example of a matrix raw and analysis pattern for a Request.

Phase	***Task***	***Request***	***Description***	***Code***	***Status***	***More details***
I	I_T1	Is it possible to import an STL file?	While importing a file in the CAD model environment, the .stl extension should be among the options	I_T1R1	Yes	

Investigated Requests and Achieved Requests can be used to evaluate software behavior through the Phases of the workflow as well as to obtain summary data of the TS. Those elements can be manipulated to perform the design tools selection as described in the evaluation approach application section.

1.3 Overview of Requests details

The most relevant Requests for each matrix are going to be summarized. Table 2 reports an overview of KPIs matrices composed of four summary tables related to the four analysed phases. Each of them reports KPIs expressed by Tasks and the associated Requests to deal with into the matrices.

Table 2. Summary tables of KPIs matrices.

I. Geometry preparation	
Task	**Requests**
Design space & Non-Design space definition	file import, geometry modification, features management, design areas for different bodies, surfaces or volumes splitting, features for non-design areas creation, regions with special structures (e.g. latticing, cellular structures etc.)
Material definition	material editing, material anisotropy, temperature dependent data for thermal simulations.

II. Optimization Setting	
Task	**Requests**
Mesh creation	element type, mesh element size, several meshes, mesh properties control, mesh quality check, mesh quality improving, elements and nodes numbering, mesh configuration save/reuse, rigid elements creation.
Loadcases definition	thermal loads, connections, loads/restraints support type, load distribution/spatial variation, association by sets, multiple loadcases, preliminary structural analysis, analysis type selection, model check.
Optimization setup	different design objectives, multiple objectives, design constraints, multiple design constraints, shape constraints, manufacturing constraints, AM constraints, printing direction, min/max structure size, filling structures, optimization algorithm parameters setting.
Solving & errors	error display, error explanation, problem cause tracing, computation parameters setting, CPU usage set, computation history along cycles, time needed to perform cycles, computing duration estimation, optimization report, working while optimization is running.

III. Results and post processing	
Task	**Requests**
Results display	result preview, relative density adjustment, result mass check, result of each cycle, cycle-result exploitation, result data visualization, shapes comparison, result of design objective, data in case of failure.

Geometry generation	generating geometry, density threshold setting, geometry shape improvement, overhang control preservation, mass target deviation, geometries and data comparison, geometry update by editing initial model.
Post-processing	generated geometry modification, ready to print possibility, overhanging features display, shape analysis, generated geometry simulation, TO information retrieving, final geometry export, export formats.

IV. Interface	
Task	**Requests**
Input data & workflow	feature tree along setup, input data edition on tree, summary of input data, editing data by summary, driven optimization, assistive toolbar, missing step/not complete warning, cloud data storage, workspace customization.

2. Case Study and Tools Systems assessment

In order to embrace the redesign of an automotive component to be produced by metal AM technologies, the method's application is arranged as follows:

- The redesign project is defined and a simplified model is created;
- The model is concurrently developed by means of four different TSs;
- The assessment method is applied for tools selection scope.

Afterward, the final redesign can be performed through the definitive model enriched by further design and simulation steps and a systematic approach to exploit the potentials of the selected TS. The optimization study, therefore, retraces the above-described tasks of the TO workflow: Geometry Preparation; Optimization Settings; Results and Post-processing.

2.1 ICE piston redesign

The redesign subject is the piston of a single-cylinder Internal Combustion Engine (ICE). The application is an interesting example of lightweight design in order to improve engines performance and efficiency. The analyses (e.g. functional analysis, assembly analysis, finite element analysis, etc.) of the original component return the objectives and constraints of the project. The material selected is the AlSi10Mg aluminum alloy suitable for PBF processes. The design objective is a 15% mass reduction together with structural stiffness preservation.

2.2 Tools Systems selection

Four different TSs are selected to develop the optimization of the case study. Each of them is commercial software so that it is both available on the market and accessible by users and companies for DfAM implementation. The benchmarked TSs are Dassault Systèmes 3DExperience [5], Siemens NX [6], Autodesk Fusion [7], and PTC Creo [8], hereinafter respectively identified as TS-A, TS-B, TS-C, and TS-D. They are configurable CAD platforms to support the design process by combining modelling, simulation, and data management through the possible integration of CAD, CAE, CAM, and PLM tools. Actually, all of them represent software from the state-of-art for TO integration into the computer-aided design phase, suitable for DfAM implementation. The TSs list is quite comprehensive, but a remark is that additional software can be considered, as well as such tools are continuously evolving to support designers' aims, as previously discussed.

2.3 *Topology optimization*

The reference finite element model to be considered for ultimate analyses and validations is composed by four load cases: Top Dead Centre during Combustion (TDCC); Top Dead Centre at the beginning of the Induction stroke (TDCI); Left and Right Piston Thrust (LPT, RPT).

To compare studies to be performed among different TSs, each of them has been performed using the same parameterization. A simplified model of the piston has been defined so that each software used will fit with the optimization settings. This simplified model is based on the most basic FEM tools, such as:

- Forces and pressures as structural loads;
- Fixed displacements as structural constraints;
- Half-geometry of the piston model.

Moreover, as every optimization software can't afford to perform multiple case analysis, a single one will be considered, resuming the key elements of the previously defined load cases.

TO1 – Geometry preparation. Geometry preparation requires the initial CAD models design to achieve the correct Design Space definition and the AlSi10Mg alloy for PBF material definition. In particular, piston crown, pin housing, rings housings, skirts are set to keep a minimum thickness. Figure 3 depicts the simplified model Geometry Preparation phase performed on the different TSs and it shows the different approaches for the Design Space and Non-Design space definition.

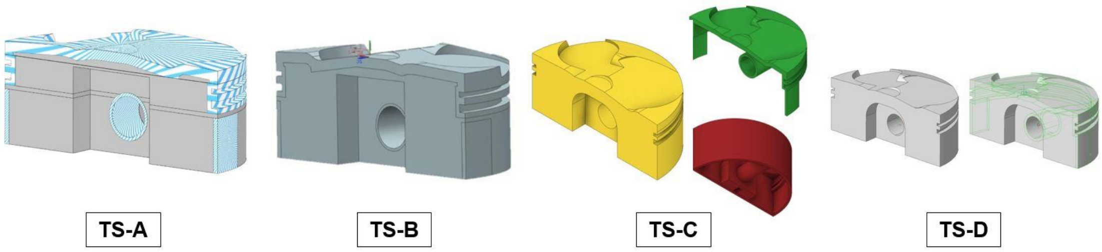
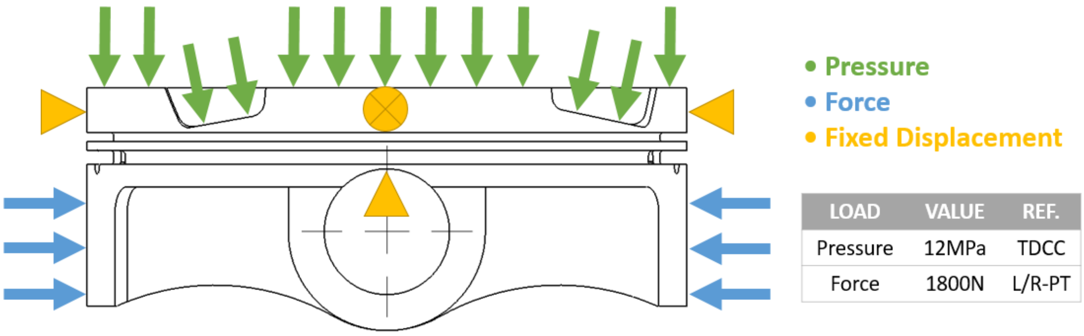


Figure 3. Design Space model respectively from TS-A, TS-B, TS-C and TS-D.

TO2 - Optimization settings. As explained before, the simplified model is based on a single load case, resuming the key elements of the four reference load cases. Figure 4 provides the loads and constraints definition by analytical calculation and the FEM scheme setup on the different TSs. The load case is modeled in the worst case considering the maximum possible load related to engine working conditions (e.g. 12 MPa comb. pressure, 14000 rpm).



LOAD	VALUE	REF.
Pressure	12MPa	TDCC
Force	1800N	L/R-PT

Figure 4. Load Case of the simplified Finite Element Model.

As the topology optimization will be performed only with half of the piston, symmetry boundary conditions must be added to the model. Thus, fixed translation displacement constraint has been added to the normal of the symmetry plane and fixed rotational constraints have been added to the axes lying on the symmetry plane. The optimization algorithms are set up to minimize parts compliance (target) for a given mass (constraint) that is calculated to achieve a 15% weight reduction.

TO3 - Results and Post-processing. Figure 5 provides preliminary FEA results of the geometries generated by the optimization software. Where possible, automation is exploited to generate a solid model, therefore limiting or potentially avoiding manual geometry redesign.

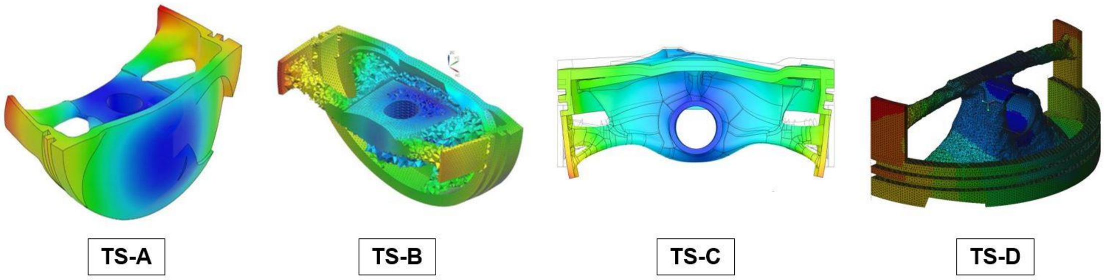


Figure 5. Preliminary Finite Element Analysis of results respectively from TS-A, TS-B, TS-C and TS-D.

In some cases, this feature is not allowed by the software, and design interpretation is required. Moreover, this step becomes necessary to achieve even a preliminary validation with respect to models stress. Figure 6 depicts the TO workflow output, to be further improved according to additional simulations and industrialization tasks.

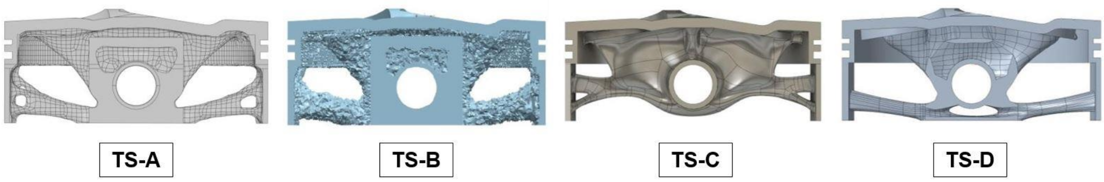


Figure 6. The Topology Optimization results respectively from TS-A, TS-B, TS-C and TS-D.

2.4 Assessment of Tools Systems

The procedure to apply the proposed approach is now described. Hereafter the expected output type and the data obtained are described. Method application is based on direct and simple interaction with the KPIs matrices and for each Request selected (see 1.2, Table 2), its fulfilment by the TS has been studied through the topology optimization case study. Once all the four KPIs matrices have been filled-in, it is easy to build a summary table with the results. Table 3 returns the level of satisfied Requests for a generic product-process design integrated platform.

Table 3. Summary table for a generic TS.

Phase	GP	OS	R&PP	IT	TOTAL
Investigated Requests	13	46	24	10	93
Achieved Requests	10	33	17	6	66
AR%	77%	72%	71%	60%	71%

Values related to the different phases that compose the workflow can be obtained, as well as summary data of the evaluated TS, such as the number of Investigated Requests and Achieved Requests. For each TS, starting from considering Requests (see 1.2, Table 2), Investigated Requests is a subset representing the number of Requests that are answered during the investigation. Whereas Achieved Requests is a further subset bringing the number of Requests that are satisfied. Then, to evaluate and pair those results, a percentage of Achieved Request (AR%) can be calculated. In this way, software behavior along the process becomes immediately visible.

Moreover, starting from Achieved Requests, output data can be used to structure Summary Charts that produce a visual impact of software behavior, as depicted in Fig. 7. Specifically, Fig. 7a immediately returns TS potentials about the four analyzed Phases, while Fig. 7b graphically represents a deepened focus on the specific Tasks. These allow to monitor software behavior with respect to specific Phases or Tasks (or rather KPIs), to meet specific designers' and projects' needs.

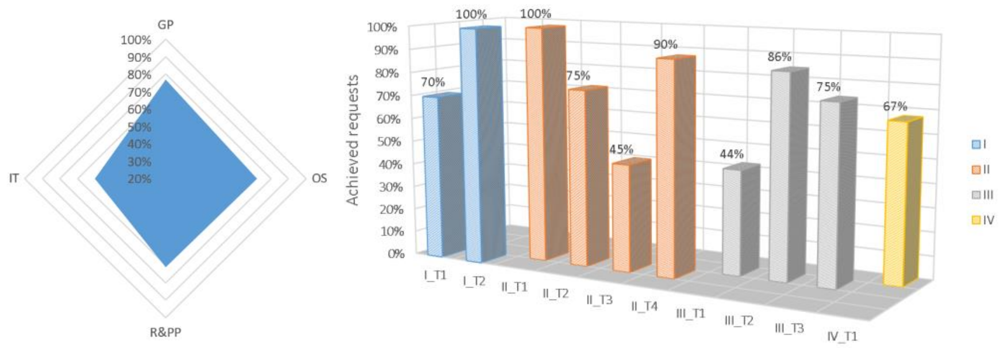


Figure 7. On the left side, the Phase-focused Summary Chart (a); on the right side, the Task-focused Summary Chart (b) for a generic TS.

3. Results

Output data obtained from method application can be further manipulated. KPIs matrices actually represent an evaluation element for design tools. For example, data related to software evaluation can be used for the selection of tools for topology optimized components design.

Not only Summary tables percentage of Achieved Requests can be compared, but also the homogeneity of scores can be evaluated, as well as it is possible to assign weights to different phases and further manipulate data to meet specific needs of the design. As shown and Fig. 8, data can be combined in order to compare tools involved in the workflow.

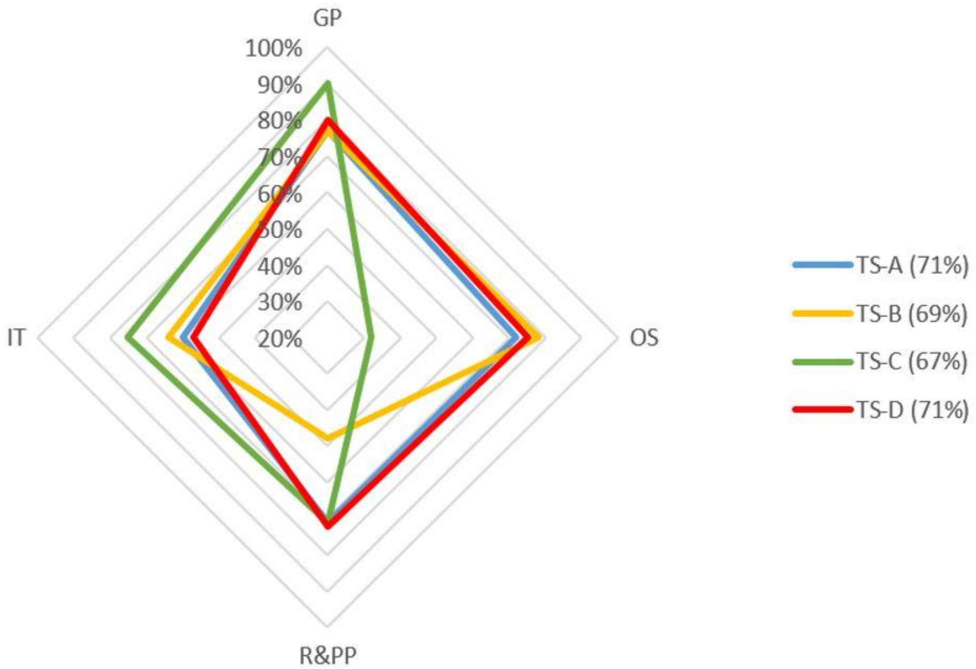


Figure 8. Comparison of Phase-focused Summary Charts from the investigated TSs.

The TS-A, TS-B, TS-C and TS-D have been used for the evaluation method application (2.2). Summary tables provide detailed data and return the different scores related to the different phases of the TO workflow. The percentage of Achieved Requests shows the trend of the performance of the tools along with the workflow phases. Moreover, the Phase-focused Summary Charts can be considered. TS-B shows good optimization settings and interface but poor results usability. TS-C is the most user-friendly but it lacks optimization settings contents. Both TS-A and TS-D present the highest total percentage of Achieved Requests (71%). Nevertheless, by comparing the Phase-focused Summary Charts, TS-A shows a more regular trend along the workflow, since it has fewer weak points. By avoiding assigning weights to different Phases or Tasks, TS-A is selected in order to perform the product development of the topology optimized component.

4 Conclusions

Lightweight and functional design, and potentials offered by the combination of TO techniques and AM technologies have been described in this thesis. Current TO issues and challenges have been summarized and the connection between design approaches and tools capabilities for actual applications has been highlighted. Thus, since the need for assessment approaches to select proper design tools is relevant, a method for this purpose is presented. It is based on KPIs matrices connected with the tasks to implement TO. It relies on clarity and impartiality principles for the sake of objectivity and it is built with the idea of being expandable and customizable to guarantee flexibility and a wide range of applications. In particular, KPIs can be selected and different weights can be assigned to meet different designs and projects needs. An automotive ICE piston is the case study for a redesign based on TO, which is concurrently set up through four different commercial software at the state of art. The assessment approach is therefore applied and the four benchmarked TSs are compared to select the platform to perform the final product development. The approach can be used to evaluate either CAD platforms or different arrays of standalone tools, as well as it can be used to monitor software development over time, since it has universal applicability. Therefore, the method can sustain the key design tools selection phase for DfAM, as well as the CAX platform selection for industrial settings embracing AM technologies. Further developments cmay concern the approach extension to subsequent phases of a DfAM workflow, such as product simulation, build preparation or process simulation, etc. Considering both product optimization and process optimization, it could be possible to support holistic methodologies such as the 'Simulation driven integrated approach' for the design and manufacturing system.

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