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The economics of additive manufacturing and topology optimisation – a case analysis of the electric scooter

Rayko Toshev[a], Nikos Kolatsis[a], Ahm Shamzzuzoha[b,c] and Petri Helo[a]

[a]School of Technology and Innovations, University of Vaasa, Vaasa, Finland; [b]Digital Economy Research Platform, School of Technology and Innovations, University of Vaasa, Vaasa, Finland; [c]Faculty of Graduate Studies (FGS), Daffodil International University, Daffodil Smart City (DSC), Ashulia, Dhaka, Bangladesh

ABSTRACT
This article describes the process of topology optimisation (TO) of three components of an electric scooter, namely the neck, platform, and suspension bracket. We use these example parts to investigate the additive manufacturing (AM) workflow, from re-design to nesting and support approach that has an impact on the total costs and time required for product development and manufacturing, with a focus on Direct Metal Laser Sintering (DMLS) technology. Due to the mathematically generated shape, components that are topology optimised and fabricated through AM have improved structural load-to-weight ratio. The article elaborates on the cost of manufacturing these new geometrical structures and re-designing existing components. Recognising topology-optimised design features for the LPBF manufacturing process like creating touch points between parts in 3D nesting orientations and lattice structure integration reduces cost in volume production. Our study shows that it is beneficial for the DMLS process to perform finite element analysis (FEA) and optimise components using TO and lattice structures, as weight reduction also translates to cheaper fabricating parts. Defining and implementing a streamlined workflow for editing the complex automatically generated support structures improves manufacturability. Such approaches encourage companies to adopt wider LPBF processes in mainstream industries.

Abbreviations: AM = additive manufacturing; DMLS = direct metal laser sintering; TO = topology optimisation; SLS = selective laser sintering; FEA = finite element analysis; CAD = computer-aided design; CAM = computer-aided manufacturing; 3D = three dimension; CAE = computer-aided engineering

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Additive manufacturing; topology optimisation; lattice structures; direct metal laser sintering; finite element analysis

1. Introduction

Traditionally, there are available methods and manufacturing processes used for achieving weight reduction and strength improvement in manufacturing industries. For instance, the cold rolling process can be deployed to improve the tensile strength and microhardness of products due to density dislocation and applied strain (Rahmatabadi et al. 2021). Another

CONTACT Ahm Shamzzuzoha ahsh@uwasa.fi

process known as superimposing ultrasonic vibrations contributes to increasing hardness and reduction in the average grain size of products (Najafizadeh et al. 2021). Moreover, metal matrix composites exhibit a high ratio of strength with weight and excellent wear resistance. Furthermore, a forming process also focuses on designing lightweight material by replacing the primary material with another material with improved weight characteristics (Rosenthal, Platt, and Hölker-Jäger 2019; Prabhu et al. 2020; Rosenthal, Maaß, and Kamaliev 2020). On the other hand, AM or 3D printing sometimes called also direct digital manufacturing, is a manufacturing technology, which enables companies to produce components from the digital design without traditional tooling or molds required. These technologies produce components by joining volume elements in layered deposition or solidification (Gibson, Rosen, and Stucker 2010; Pradel et al. 2018b).

AM technology, which was originally introduced in the late 1980s to facilitate rapid prototyping, has applications in low-volume production across various industries such as aerospace, aviation, the medical industry, etc. (Wohlers and Wohlers, 2013). AM design engineers are coming across new challenges, such as the growing complexity of designing components and the requirements for lighter parts that can bear the same physical forces (Prabhu et al. 2021).

One solution is to use the advancement in TO to achieve optimal structural performance. The TO algorithm takes the 3D model, boundary condition, loading, and performance objectiveness as input to optimise the structure of the chosen parts (de Siqueira, Mozgova, and Lachmayer 2018; Montemurro 2022). AM market has been growing steadily over the last decade and also its designing tools have evolved in terms of ease of use, computational capabilities, and affordability.

Due to the wide number of possible applications across various industrial sectors, there is a need for comprehensive case studies on parts to investigate where this technology is applicable, based on its capabilities and cost. Current studies show that AM is suitable for low and medium-size production volumes and highly customised products avoiding the need for special tooling. In addition, for products that have been ramped down or in spare part supply chains, 3D-printed parts can become economically viable. (Jia et al. 2016; Pradel et al. 2018a).

This article examines the process of re-designing electric scooter parts using TO and lattice structures integration to generate lightweight optimised components for DLMS manufacturing, that can be retrofitted to the vehicle. A cost comparison is done between additive and subtractive production processes. We also consider different nesting strategies for manufacturing and analyze how they affect the price.

2. Literature review

2.1. Topology optimisation and lattice research

AM originated as rapid prototyping technology (Gao et al. 2015; Gibson 2017). It is used to create complex shapes, building a part layer by layer (Pereiraa, Kennedy, and Potgieter 2019). All AM processes use digital 3D models. Both the manufacturing interface and material deposition are fully computer-controlled. In contrast, subtractive manufacturing techniques remove material through various operations such as machining, drilling, or grinding techniques. In general, AM allows for greater freedom of design compared to traditional manufacturing (Conner 2014). TO is a computer-assisted method deployed in product development for design optimisation (Sigmund and Maute 2013; Schuh et al. 2020; Roiné, Montemurro, and Pailhès 2021; Bertolino and Montemurro 2022).

2.1.1. Topology optimisation by isotopic material

TO assist the designer to achieve optimal distribution of structure or material according to a set of constraints. This final structure is eventually optimised by developing several voids and solid areas within the designing domain according to the forces acting upon the model. In general, any optimised design initiates with minimum design compliance. TO aims to generate a complex structure with less weight along with maintaining the required stiffness and compliance. (Van Dijk, Langelaar, and Van Keulen 2010). Allaire, Bihr, and Bogosel (2020) proposed a shape and topology optimisation algorithm, which was based on the level set method and shape derivatives computed by the Hamamard method to minimise the structural volume of products while maintaining efficiency. Montemurro and Refai (2021) proposed a Non-Uniform Rational Basis Spline (NURBS)-based Solid Isotropic Material with Penalization (SIMP) method to deal with heat conduction problems formulation of a CAD-compatible topology optimisation method. Costa et al. (2019, 2021) studied a broad topology optimisation approach that is based on a fusion of the NURBS hyper-surfaces formalism and a well-known density-based method.

2.1.2. Evolutionary structural optimization (ESO) and bi-directional evolutionary model optimisation (BESO) methods

Xie and Steven (1993), first introduced the evolutionary structural optimisation (ESO) method. The basic principle of ESO is related to a simple and empirical concept of a structure evolving into an optimal condition by slowly removing (hard-killing) elements with the lowest stresses (Xie and Steven 1994). Different kinds of structural problems are solved by using the ESO model and the results are matched with the solutions through traditional optimisation models (Huang and Xie 2008). The ESO method is very easy to programme in a software package. Moreover, in this area have been developed different kinds of methods try to improve the algorithm in TO. However, we should underline that if that material is being removed from the beginning of the algorithm, the ESO is not capable of recovering elements that have been deleted in advance. The bi-directional evolutionary model optimisation (BESO) approach is an extension of the first idea of (ESO) that allows the addition of new elements in the locations next to those elements with the highest stress (Yang et al. 1999; Huang and Xie 2008). This ESO-BESO model has been used in a wider variety of applications (Zuo, Xie, and Huang 2009).

2.1.3. Lattice structures

A lattice is considered a design structure, generated through repeating a unit cell. Lattices are used by design engineers to replace solids inside a part (Derakhshanfar et al. 2018; Montemurro, Bertolino, and Roiné 2021). It is possible to remove material from some non-critical areas of any component while keeping the required stiffness. It is generally estimated that lattice integration can reduce the total mass by up to 90%. Different types of lattice structures exist, based on various characteristics like self-support or aesthetics.

Research on intricate and intriguing lattice structures has grown and major CAD design software updated versions have their integration included as a standard feature. Using

(DMLS) technology self-supporting lattice structures can be directly manufactured from a range of metal powders including aluminum. Quaddiametral lattice is self-supporting in DLMS and the only available type as integration inside the TO structure for the chosen software. Quaddiametral lattice was used in the case because it is self-supporting in the DMLS process and its range of unit cell volume and size fraction can vary based on the TO solution.

It is noticed that the mechanical behaviour of the 3D printed structures is dependent on both the relative density and intrinsic material properties. Various lattice structures are 3D printed and tested under both static and dynamic loading, which shows interesting results. For instance, octet-truss lattice structures were tested through specific Energy Absorption (SEA) of the lattice structures that resulted in increased monotonically with relative density. Maskery et al. looked at the mechanical behaviour of ALSi10Mg lattices that were graded and uniform under quasi-static loading. The findings suggested that graded lattice architectures were favourable for absorbing energy. Through experimental testing and numerical simulation, Xiao et al. examined the quasi-static and dynamic compressive behaviour of the Ti-6Al-4V lattice structures. The findings indicated that there was some relationship between the peak stress and the rate of loading.

2.2. Design for additive manufacturing (DfAM)

Rapid prototyping or additive manufacturing (AM) is a production method that uses a 3D printer to build parts through digitally controlled layer-by-layer deposition (Kumar et al. 2019). It is considered one of the most promising technologies for the future. By minimising material waste and time to market, the AM technique is a technology that claims to lower part costs. Additionally, AM can enhance design flexibility and options, which reduces weight and makes it easier to produce complex parts (Coykendall et al. 2014; Karayel and Bozkurt 2020; Prabhu et al. 2022). Design for additive manufacturing (DfAM) can be an updated version of traditional design for manufacturing and design for assembly, which requires different types of features with various constraints (Pradel et al. 2018b; Fillingim et al. 2020). To implement DfAM, vast knowledge of design guidelines, process specifics, essential tools, and post-process treatments is needed.

Laverne et al. (2015) compare the outcomes of the introduction of DfAM knowledge to three groups of designers: (1) a control group without DfAM knowledge, (2) novice designers exposed to DfAM information through memos and artifacts, and (3) novices paired with AM specialists. Similarly to this, Fillingim et al. (2020) talk about how designers with different degrees of expertise perform when DfAM information is introduced through design heuristics. They note that when given DfAM criteria, professionals in the sector produced more innovative concepts than inexperienced student designers. Another study by Hwang et al. (2020) compares the effects of delivering DfAM-based design principles on the ideation performance of novice and expert designers. In their experiment, they found that when given the DfAM principles, experienced designers produced concepts that were more original than those of less experienced designers. DfAM is evolving as metal 3D printing machines excel in use in sectors like automotive, aeronautic, and medicine (Salem, Abouchadi, and Elbikri 2020). Paul and Ginson studied DLMS in the bicycle industry using stainless steel 316 and titanium 6Al.4V as the baseline material.

2.2.1. Advantages of additive manufacturing

AM offers several fundamental features which lead to significant advantages over conventional manufacturing methods and act as the driving force behind its growth. With the advantages of this technology, metal materials have advanced greatly in addition to polymer materials. Numerous different metals, alloys, and ceramics can be processed using it (Sames et al. 2016; Gardner 2023). Some of the advantages of AM are shorter lead time, customised design, functionally optimised products, quicker design change, lower inventory level, waste reduction, small production batches, etc. Mass customisation and parametric designs can be achieved in AM because there is no need for making additional molds or extra tools.

Both metallic and non-metallic products are printed using AM technology. The designers enjoy almost unrestricted freedom to design through AM principle, which is cost-driven (Atzeni et al. 2014; Hagedorn et al. 2019). AM is evolving with various processing mechanisms to strengthen its quality, for instance, in the laser sintering mechanism, where metallic or non-metallic components are developed through a fusion powder bed to manufacture components layer by layer (Ngo et al. 2018; Sonkamble and Phafat 2023). It is possible to develop various complex components with AM machines. It is also possible to change the internal topology of the components by reducing weight but improving stiffness while maintaining the functional specifications. Such developed components offer higher mechanical performance in terms of their weight, which is impossible to do with traditional processes (Salem, Abouchadi, and Elbikri 2020; Praveena et al. 2022).

This AM technology has been widely applied in the aerospace industry to design and develop critical components with optimised stiffness and quality (Townsend et al. 2018; Aage et al. 2017; Opgenoord and Willcox 2019; Madhavadas et al. 2022). Synthetic bone has been designed by AM, where new biomedical lattices are produced to improve the functionalities of intervertebral fusion devices (Barba, Alabort, and Reed 2019; Yan et al. 2019; Jahadakbar et al. 2020; Rouf et al. 2022). AM also shows substantial progress in the food industry for food design and food manufacturing (Portanguen et al. 2018; Scheele, Binks, and Egan 2020). In recent days, 3D printing is considered one of the most promising technologies for the future. This up-to-date technology is widely used for several purposes such as building walls, human implants, medicines, and even the food industry (Li et al. 2022; Gardner 2023; Awad et al. 2023; Makhesana and Patel 2023).

In general, it is expensive to design and develop a single product rather than mass-customised products. Moreover, the production cost of a product becomes cheaper when it is produced from the same machine or follows the same manufacturing process. This phenomenon is known as ‘economy of scale’ (Dawson 2006). In general, in the traditional manufacturing process, the majority of the costs are involved in tooling costs as well as mold costs. The principle of 3D printing is suitable for producing products in a single piece or small batch. In terms of cost, the economy of scale for 3D printing does not change from producing one product to millions of products (Anderson 2012; Costabile et al. 2017; Cardeal, Leite, and Ribeiro 2023).

2.2.2. Limitations of additive manufacturing

There are undoubtedly many advantages, including the capacity to print intricate structures, design freedom, ease of use, and product customisation using AM. However, AM technology has not yet developed to the point, where it can be used in practical applications. There have been downsides and difficulties that call for further inquiry in addition to technological advancement (Abdulhameed et al. 2019). The limitations or challenges that require more research and analysis include the cap on part size, anisotropic mechanical properties, construction of overhang surfaces, high costs, poor manufacturing efficiency, poor accuracy, warping, pillowing, stringing, gaps in the top layers, under-extrusion, layer misalignment, over-extrusion, elephant foot, mass production, and restrictions on the use of materials (De Jong and de Bruijn 2013; Chen, He, and Yang 2017). Additionally, AM technologies can be identified in a limited range of raw materials, parts certification, quality assurance, finishing and post-processing, the high price of equipment, and the limitation of machine build volume, especially for metal AM (Khajavi et al. 2015).

Moreover, the emergence of the staircase effect or stacking mistake in the produced parts is one of the main hurdles in the AM process. For internally manufactured surfaces, this kind of inaccuracy is negligible, but it significantly lowers the quality of external surfaces. Although there are other procedures (post-processing), such as sand sintering, that can be used to reduce or eliminate this defect, doing so also lengthens the process and raises the cost (Abdulhameed et al. 2019; Maleki et al. 2021). Furthermore, the difficulty of a tiny build volume is something that AM technology users must also contend with. It is seen to be one of the primary drawbacks of AM technology. Generally, the huge components are reduced in size or divided into smaller pieces, which takes more time and work. Most of the time it is neither practical nor efficient to scale down the model. If adhesives are utilised, the assembled subparts have reduced strength after scaling down, or they become bulky if mechanical fasteners are used (Easter, Turman, and Sheffler 2013; Gao et al., 2015).

3. Re-design parts comparison, results, and analysis

3.1. Re-designing the scooter 'neck' connector

For this part, we are using TO and lattice integration to generate a design optimal for DLMS production. FEA analysis was used for checking the stiffness after the optimisation. After designing the 'neck' using CAD software NX Siemens, the process continues with Altair Inspire software (FEA and Optimization for Design Engineers). The main goal of the performed TO process is to decrease the weight while retaining the load case. To fulfill this objective, the part is defined in the design space to remove the necessary material. Therefore, in Figure 1 (b), the first task is defining the area that is considered to be partitioned out and is not considered in the optimisation.

After defining the design space, the process then moves forward to define fixtures, which are at the end of the part. The definition and directions of the physical forces, contact points, and surfaces are described in the user interface. The necessary load is then applied from both sides. The amount of load is considered 1500N. Such loads are generated externally for one moment in the entire part. Figure 1 (b) displays the design space, force loads, and partition out.

Initially, AL Aluminium was selected for the TO redesign, being lighter not rusting metal, commonly used in the DLMS process and automotive industry. However, being highly reactive, it is more demanding in manufacturing means and 3D printing requires Argon Gas, ATEX-certified storage and printing facilities. Compared to SS Stainless steel 316L

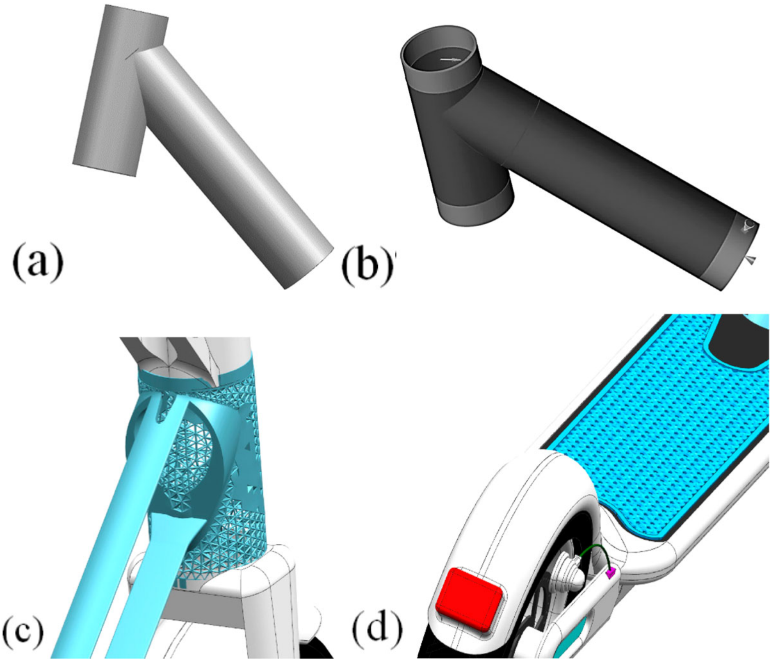


Figure 1. (a) Display of E-scooter neck part (dimensions 170∗120∗65 mm) before necessary modification (b) Display of defining TO design space, force loads, and partitions out of the neck part (c) is a view of the neck after TO and variable quad lattice integration and (d) displays the platform.

Table 1. Results from four types of optimisation of scooter neck.

Name	Objective of analysis	Value	Weight kg.	Factor of safety
The original part before re-design			0.132	
Optimisation 1	Maximum stiffness	Reducing the design space volume by 60%	0.079	> 1.5
Optimisation 2	Maximum stiffness	Using full design volume	0.086	< 1.5
Optimisation 3	Minimum mass	Using full design volume	0.083	> 1.5
Optimisation 4	Uniform tetra lattice integration	Using full design volume	0.062	> 1.5

which can be printed using Nitrogen and is a less expensive material, redesigned part manufacturability test was done using SS 316L.

AL Aluminium

Elastic Modulus (N/mm2) 0.70 • 105

Poisson' s Ratio 0.35

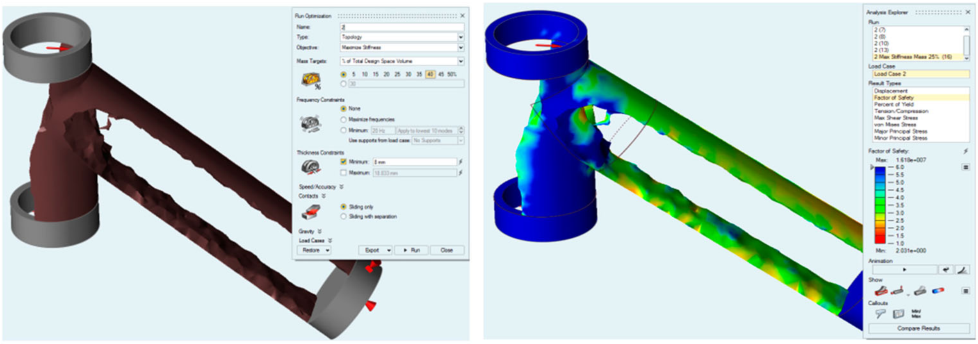
Density (tonne/mm3) 2.70 • 10–19

Yield strength (N/mm2) 35

Ultimate strength (N/mm2) 90

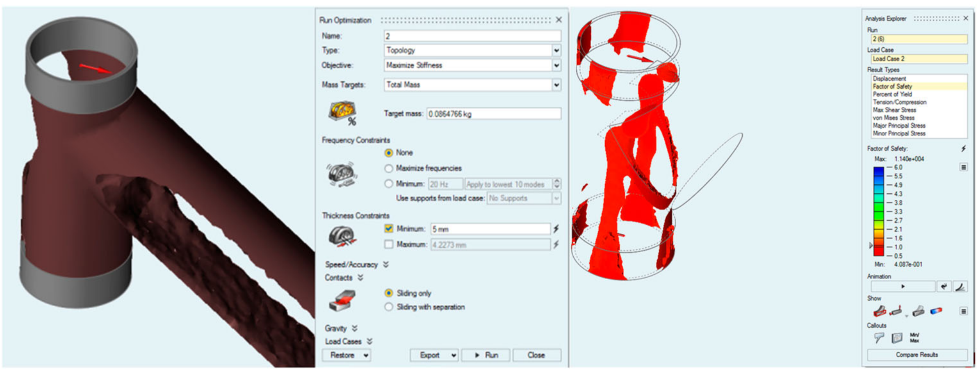
Four alternative optimisation scenarios are generated and presented in Table 1. It shows the results of four different types of optimisation processes, which can be explained as follows:

The first optimisation (optimisation 1) attempts to reduce the weight of the neck. From Table 1 it is seen that the goal in Optim 1 is, a) to achieve maximum stiffness, and to reduce



(a) (b)

Figure 2. Optimisation 1 with maximum stiffness and 40% total design space(a) and (b) results from FEA.



(a) (b)

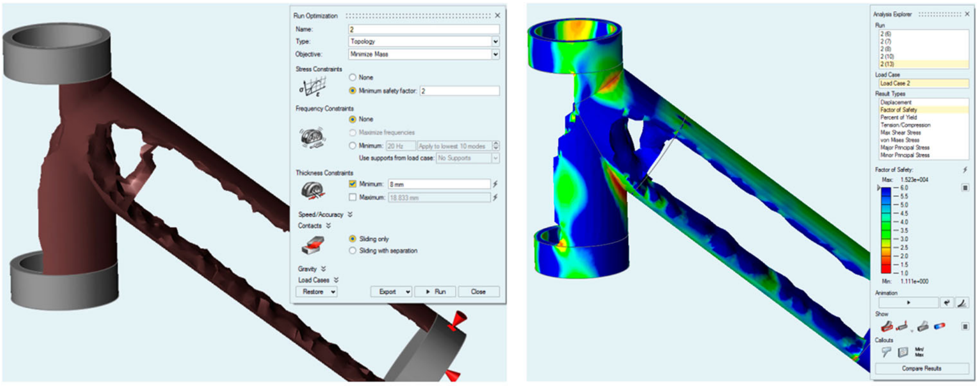
Figure 3. Optimisation 2 results with (a) maximum stiffness and total target and (b) result from FEA.

60% of the total volume, and b) to conduct FEA, which was done by using Inspire software, as displayed in Figure 2. Based on Table 1, it is seen that this optimisation option should execute a factor of safety of more than 1.5. The component is tested under specific loading conditions to ascertain its reaction.

Figure 2 also displays the limit of the scale stress factor, which is presented in red colour. Inspire software also supports the visualisation of stress through animation.

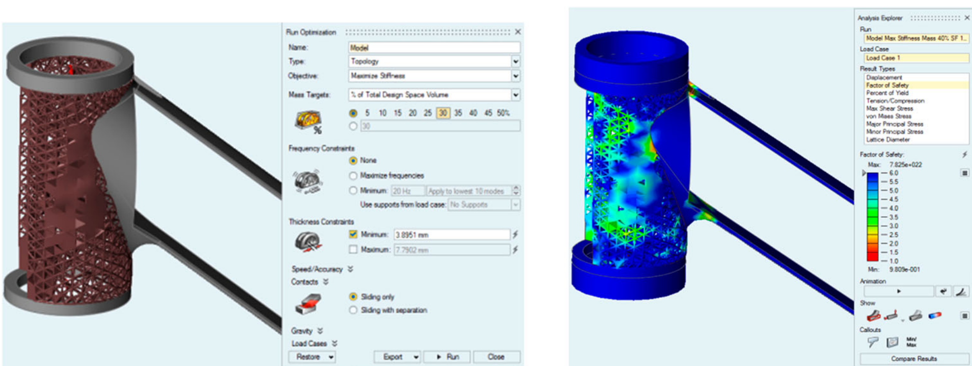
In the second optimisation (optimisation 2) the procedure is very similar to the first optimisation, except it runs with the value of TO. From Table 1, it can be seen that the total mass is reduced to 0.086 kg. Table 1 also shows that the factor of safety is reduced to less than 1.5. Figure 3 displays Optimisation 2 with its objectives, which are a) to achieve maximum stiffness, and b) to conduct FEA.

In the third optimisation (optimisation 3) Figure 4 the objectives are a) minimum mass, and b) to conduct FEA. In this optimisation process, the same load of 1500N is applied with a weight of 0.083 kg. The same load as TO is applied to the FEA analysis, which gives a factor of safety of more than 1.5.



(a) (b)

Figure 4. Display of third optimisation (Optimisation 3) attempt with (a) minimum mass and maximum stiffness, and (b) results from FEA.

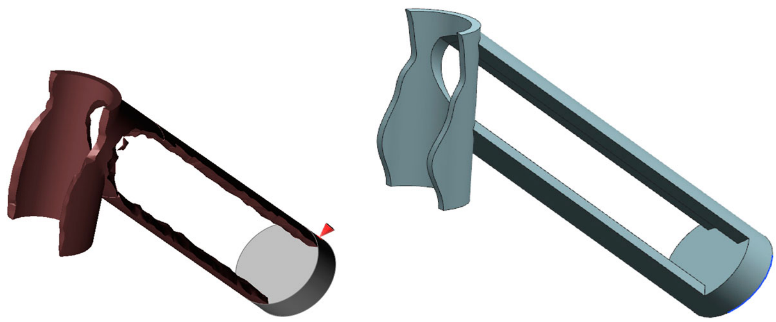


(a) (b)

Figure 5. Display of optimisation 4 with (a) lattice structure integration and (b) results from FEA.

In the last optimisation (optimisation 4), work is continued on the part to improve its strength further by deploying a lattice structure. This lattice structure was adopted to reduce its weight while increasing its stiffness with a factor of safety of above 1.5 Figure 5 displays the simulation results through the colour of the part (almost fully blue).

To advance to the next step of optimisation, the neck part is processed with the PolyNURBS feature that allows for automatic wrap optimisation results with PolyNURBS. A PolyNURBS object represents geometry as a NURBS surface surrounded by a transparent, quad-only, poly mesh cage. The shape of the PolyNURBS object is the result of the modifications made to the cage, which can be manipulated using the cage's faces, edges, and vertices. Altair Inspire software offers the necessary support to continue with this process. However, due to the advanced 3D model, two different odd-optimised shapes of the cylinder were produced, as seen in Figure 6. Due to the complex nature of the part, its 3D model is again transferred to NX software to build the part faster with more accuracy in thickness and shape.



(a) (b)

Figure 6. Neck part with (a) 3D model TO by Inspire software, and (b) 3D model by NX software.

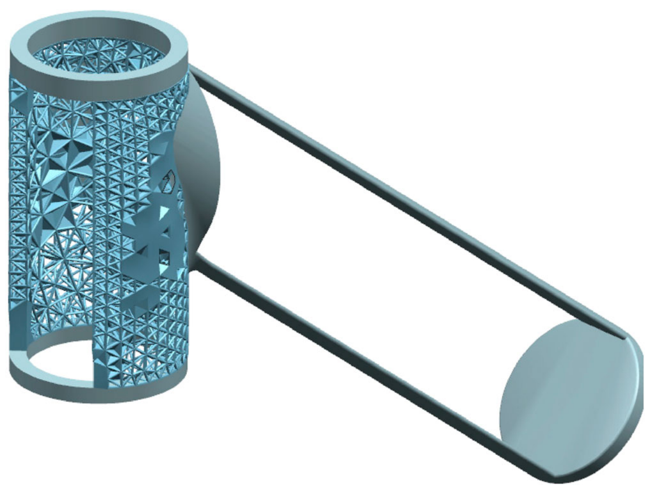


Figure 7. TO and lattice integration in the design of the neck

After that part design is adjusted for manufacturability using the polyNURBS tool to smoothen the voxels and assure unibody, variable in size and thickness lattice structure was integrated inside the solid body as seen in Figure 7. Quaddiametral lattice is self-supporting in DLMS and the only available type for integration inside the TO structure for the chosen software.

3.2. Re-designing the scooter platform with lattice integration

The same process is applied to the scooter platform (dimensions 900∗250∗50 mm) except due to its low thickness TO is not considered. We tried to achieve optimisation using lattice structure integration and analyses through FEA. Different types of optimizations for the scooter platform are presented in Table 2 displays the attempts made to achieve the best results in terms of weight-saving while exceeding the 1.5 safety factor.

Table 2. Different types of optimisation of scooter platform.

Name	Objective of analysis	Value	Weight kg.	Factor of safety
The original part before the optimisation			0.235	
Optim 1	Lattice integration	Reducing the volume by 70%	0.165	> 1.5
Optim 2	Lattice integration	Using full design volume	0.186	< 1.5
Optim 3	Lattice integration	Using full design volume	0.177	< 1.5
Optim 4	Lattice integration	Using full design volume	0.195	> 1.5
Optim 5	Lattice integration	Using full design volume NX Siemens lattice generator	0.165	> 1.5

As stated, TO is not considered for the scooter platform, but the goal is to have gaps in it. The weight of the part is reduced by replacing its solid base mass with a lattice structure. Various lattice optimisation analyses were run based on the goals, as presented in Table 2.

Figure 8 displays various optimisation options for the scooter's platform base along with the corresponding simulation Figures.

Figure 8 shows the objectives of optimisation 1 are a) to reduce weight through lattice structure, and b) to conduct FEA. It is also noticed that in this optimisation, the platform mass was reduced to 0.165, and the safety factor is very high, which is visualised from the colour of the simulation as displayed in Figure 8. The results are very acceptable; however, some other simulations can be run to ensure which one reduces the weight even more.

Figure 8 also displays the optimisation process of the platform by trying another lattice method. At this phase, the simulation results were not satisfactory after loads and stress conditions and the factor of safety was below 1.5, which is not the desired result. In Optim3, the goal is to look for another lattice optimisation for improving the part's stiffness, as seen in Figure 8. However, it is noticed that after the necessary simulation runs the new lattice structure cannot improve the factor of safety, which is below 1.5 and is visualised with red colour in Figure 8.

In Optim 4, a Thicker lattice structure was tested to achieve better stiffness, and the results were satisfactory with a factor of safety of more than 1.5 but with increased weight.

In Optim 5, a different lattice structure known as quadDiametral lattice was considered, which was based on the NX design software and presented in re 12. This specific lattice structure represents a better performance than the first optimisation due to its increased cell numbers and thickness, as seen in Figure 9.

4. Cost of AM and comparison with conventional manufacturing

Usually, it is very costly to produce a single unit and prototypes, specifically once made from metal with conventional manufacturing. At the same time mass production using conventional methods provides economy of scale and lowers the cost per unit, Figure 3 In AM, there is no need for tool replacement and the same machine can produce easily theoretically infinite model parts, unlike subtractive computer numerical control (CNC) machines. That saves time and money (Lipson and Kurman 2013). Moreover, product modifications in 3D printing are much more easily. To revise a product one only needs to change its 3D model and nothing else, which shows AM's level of flexibility (Anderson 2012).

In the case of traditional manufacturing, the majority of costs are involved with tooling costs as well as mold costs. That requires large volumes of production to realise 'economy of

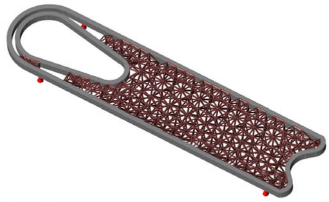
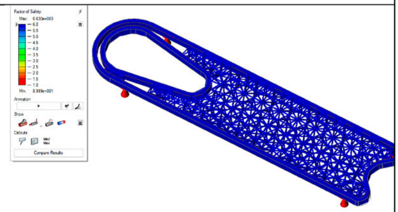
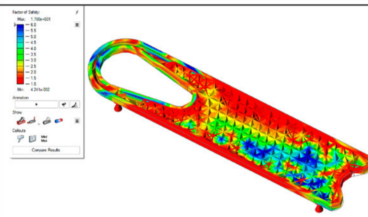
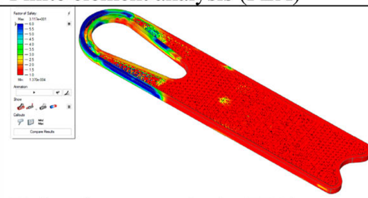
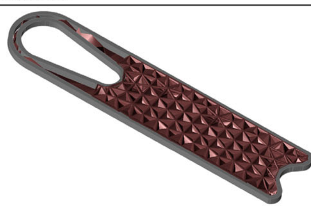
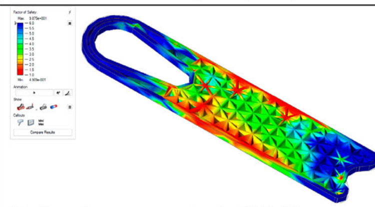
No.	Optimization option	Objective 1	Objective 2
1	Optim 1	 Lattice	 Finite element analysis (FEA)
2	Optim 2	 Lattice	 Finite element analysis (FEA)
3	Optim 3	 Lattice	 Finite element analysis (FEA)
4	Optim 4	 Lattice	 Finite element analysis (FEA)

Figure 8. Different types of optimisation of scooter platforms are based on their objectives and figures.

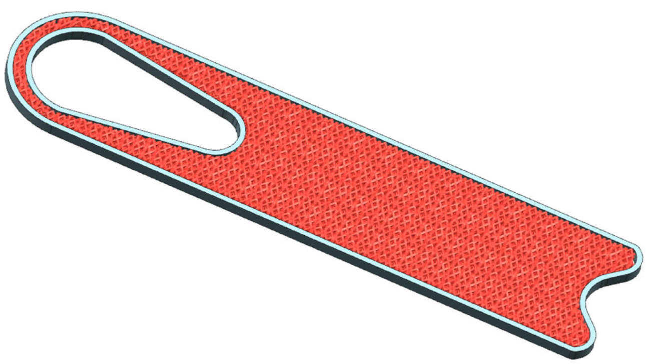


Figure 9. QuadDiametral lattice for platform base with NX design software.

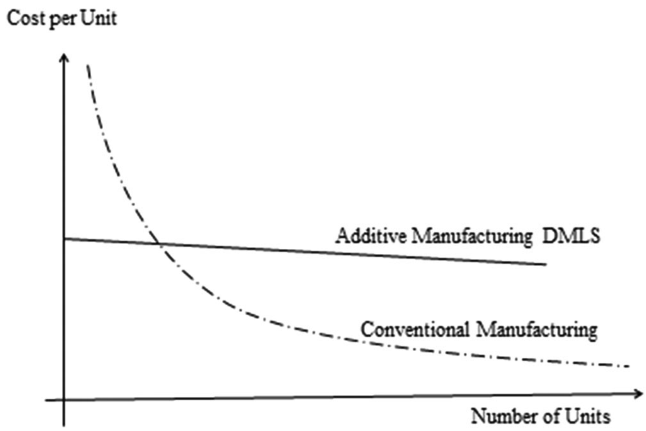


Figure 10. Display of comparisons between costs and number of units for AM and conventional manufacturing (source: authors)

scale' (Dawson 2006). 3D printing is suitable for producing products in single pieces or small batches. In terms of cost, the economy of scale for 3D printing does not change drastically, see Figure 10 (Anderson 2012).

Total cost (TC) models are applicable for AM and are the straightforward way to compare it with conventional manufacturing methods. TC is expressed in the following equation:

$$TC = VC + FC = Kr + Lw \tag{1}$$

Where TC is the total cost, VC is a variable cost, which includes the cost of labor, time, cost of tooling, etc., FC is fixed cost such as machinery cost, infrastructure cost, etc., K is capital cost such as initial investment, L is labor cost, r is the rental rate per unit, and w is wage rate per unit. Several limitations have to be considered here: Several parameters like Setup machine time, idle time, and post-processing cost are known for the DLMS process with Prima power print sharp machine and the produced parts, but not for the 3D HUB service bureau. So for the first part of the cost analysis AM vs. CNC comparison was done using an online pricing method with close algorithm parameters. For the support bracket production and 3D nesting, we used our parameters and total cost TC as in Equation 8.

The choice of adopting AM over conventional manufacturing for a specific part depends heavily on its production cost. Cost optimisation for AM manufacturing has to be accounted for during product design and development in different ways. As an example, cost-saving might come from less usage and less waste of materials, lightweight concepts in designs. from parts integration, even flexibility in delivery time, on-demand manufacturing of spare parts, and many other factors during the Life cycle assessment LCA of the part or the product (Bendsøe and Sigmund 1999).

4.1. Cost comparison

Pricing for 3D printing services on a network – manufacturing as-a-service – the marketplace is one method of valuation, we are determining network-based pricing for 3D printing services. 3D Hubs (2019) marketplace was utilised It is an online 3D environment, where

Table 3. 3D Hubs | On-demand Manufacturing: Quotes in Seconds, Parts in Days.

	Parts number	CNC Price ($)	3D Metal Price ($)
Neck part	1	271.25	596.89
	100	224.34	546.17
Platform part	1	211.47	374.58
	100	150.37	352.45

a learning model is used to recommend a pricing range for services provided by multiple suppliers. Cost analysis is performed and a comparison is made between a 3D printing approach and subtractive manufacturing of two parts (neck and platform) of an e-scooter. The total cost (TC) associated with the manufacturing system considering each category is shown in Figure 11 (Son 1991).

Analysis of the quotation prices of the DLMS printing received from 3D Hubs (2019) | On-demand Manufacturing: Quotes in Seconds, Parts in Days,' was performed. Table 3 displays the quotes of a single part and 100 parts. This price list was received from the 3D Hubs 'Get Instant Quote' On-demand Manufacturing: Quotes in Seconds, Parts in Days,' service portal, and is used for the cost comparison of the CNC machining and AM manufacturing processes of the original design of the parts. CNC is still cheaper, but cannot be used to produce a TO part. When comparing DLMS printing of the original design and the TO design, it is cheaper to produce the TO part (3DHubs 2019). From such a price comparison, AM is still more expensive to produce metal parts without considering the savings from weight reduction and benefits from increased range and performance.

The values presented in Table 3 are taken from internet quotes from 3D hubs on 10 October 2019. To evaluate the online pricing, the authors performed a separate cost analysis, based on their lab cost factors, and the comparisons highlighted in Figure 12 display the quotes for the neck part and compare the costs between traditional manufacturing, 3D metal printing, and TO/lattice design.

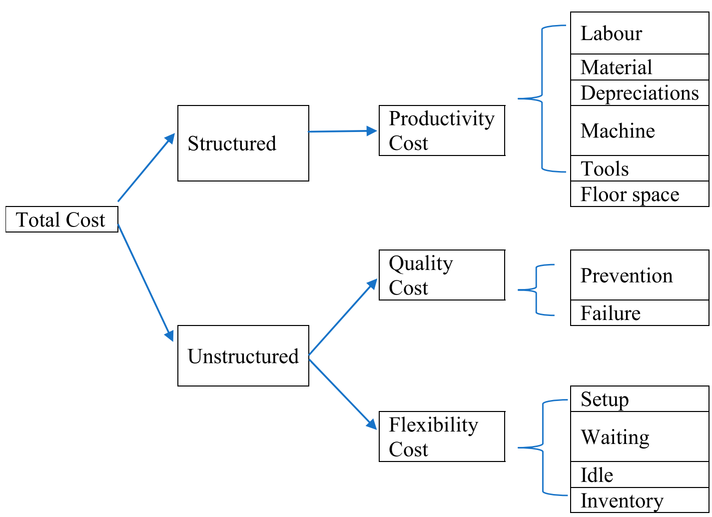


Figure 11. The total cost of an advanced manufacturing system.

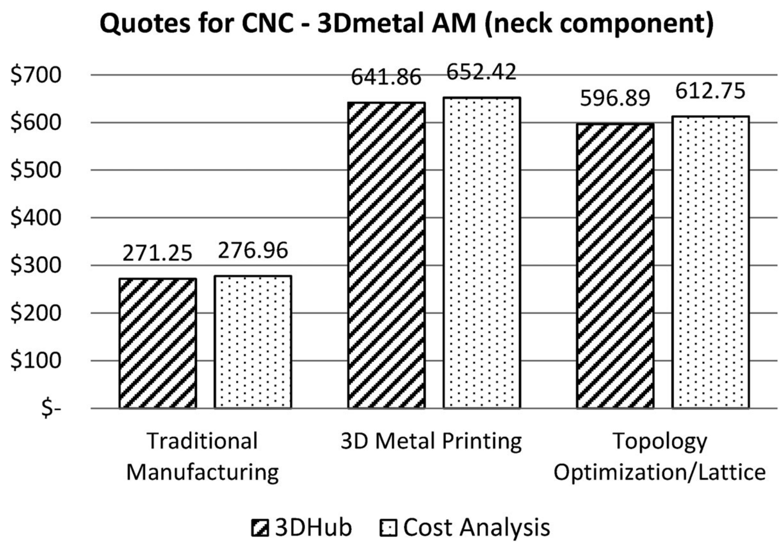


Figure 12. Price quotes for component neck for CNC – 3D metal.

Figure 12 shows that according to the 3D Hubs | On-demand Manufacturing: Quotes in Seconds, Parts in Days portal, the initial prices of the neck part were 271.25$, 641.86$ and 596.89$ for traditional manufacturing, 3D metal printing, and topology optimisation/lattice structure, respectively, whereas the calculated costs from this study were 276.96$, 652.42$ and 612.75$, respectively.

Similar cost analysis approaches are adopted for the platform component of the e-scooter and are presented in Figure 13 It shows that according to the 3D Hubs | On-demand Manufacturing: Quotes in Seconds, Parts in Days portal, the initial prices of the platform component were 211.47$, and 374.58$ for traditional manufacturing and topology optimisation/lattice structure, respectively, whereas the calculated costs from this study were 229.41$ and 338.53$, respectively (3DHubs 2019). As before, online price quotes are very similar to our cost calculations. It therefore, can be concluded that AM with lattice structure is not only better in the 3D metal printing process, but also cheaper in terms of production cost.

AM adds new dimensions of versatility in manufacturing by allowing for the delivery of highly customised goods at no additional cost penalties, and with little manual assembly work (Weller, Kleer, and Piller 2015). As Mellor, Hao, and Zhang (2014) describe the advantages of AM include new design freedom, the elimination of tooling requirements, and low-volume economics. Still to achieve a higher adoption rate in traditional industry AM need also to provide a business case in full machine capacity utilisation. As a demonstration of real DMSL printing another part, a suspension bracket (100∗35∗30 mm) was topology optimised and manufactured on a 'Printsharp 250' Prima power metal 3D printer. This 'showroom' sample part was designed and printed with the idea to physically present what kind of 'organic: looking structure FEM generates while reducing weight but still the part keeps the same function and is possible to retrofit in the vehicle. The following chapter presents the nesting strategy and cost valuation for that part in the case of single-unit production vs. full 3D printing volume utilisation business case Figure 14/Additional cost

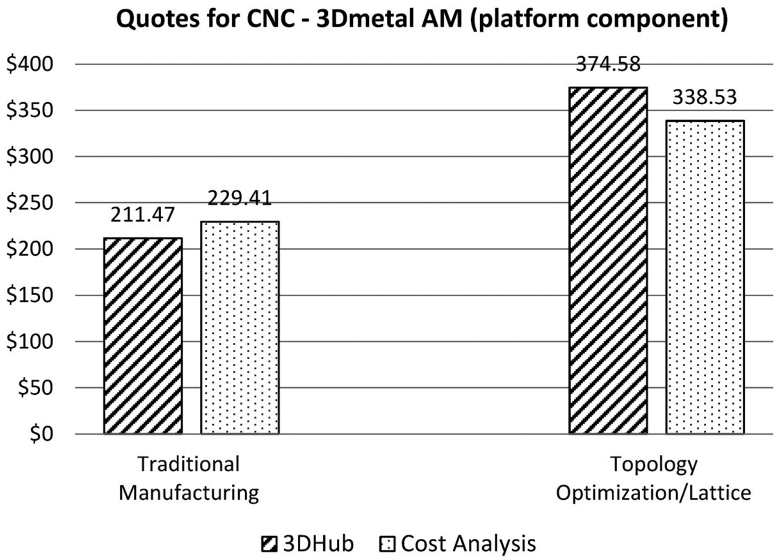


Figure 13. Price quotes for the component platform for CNC manufactured part vs DLMS part. 4.2 DMLS production and cost analysis, the effect of nesting strategies on the valuation.

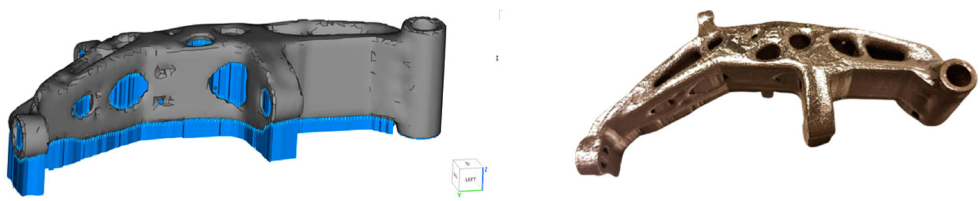


Figure 14. Topology optimised suspension bracket with generated support and the actual 3d printed part from stainless steel 316L.

analysis was conducted to study the effect of nesting in 2D and 3D. Materialize Magics software was used to position the parts and generate support structures. EP hatch slicer was used with 40 microns layer height, and 30 microns laser focal point. Stainless steel was the available material in Technobothnia AM at the University of Vaasa, Finland.

Singe part nesting a) was compared to a full stack of twelve parts in single layer b) and then to multi-layers full print volume (250∗250∗330 mm) layout c) of 144 (one hundred forty-four) parts. 3D nesting strategies are presented in Figure 15.

Each of these nests was processed on Primapower Printsharp250 DLMS printer with build chamber volume 250∗250∗330 mm. and standard printing parameters. The total cost consists of the sum of the following parameters: Material, Energy, Printer capital cost, Post-processing work steps, Tax, Manufacturer profit margin, and Order handling costs. As we have no estimation from the software for the inert gas consumption, we did not include it in the price calculator. The setup time estimate is also simplified, as print platform leveling, powder preparation; designer time, and computational time to prepare the nest were bundled in lump sum fees for pre-processing. Same way post-processing is just represented as a single fee for cutting the part off the build plate.

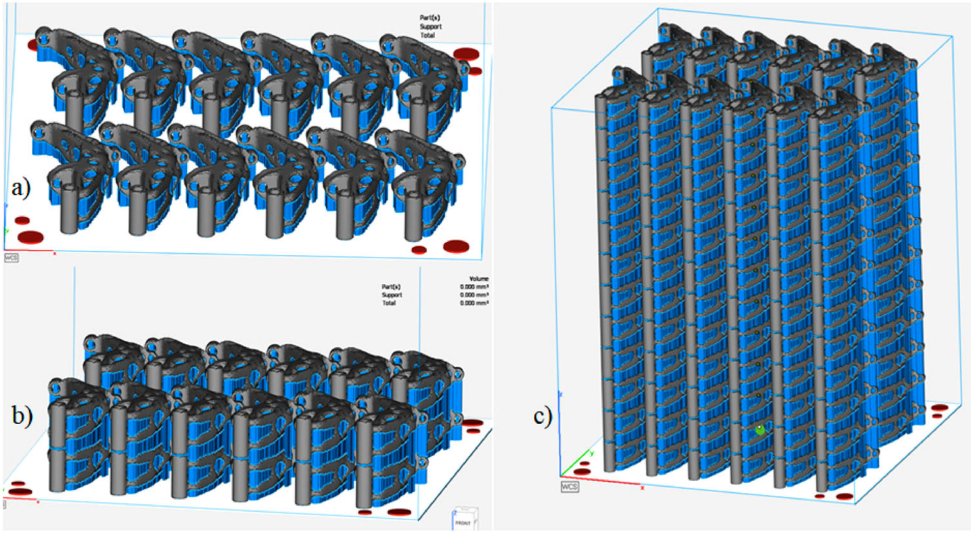


Figure 15. Nesting strategies: a) single 2D layer vs b) double layer vs c) full volume 3D stack with generated support.

The build time estimate for the single part amounted to 3 h and 40 min. The volume of the part and support was 120 cubic cm. These values were used together with energy consumption, pre, and post-processing (machine setup and curing the parts off the build plate) plus a 24% VAT tax used to calculate a total cost of 703.58 euros Figure 16.

For the single-layer nest with 12 parts, the estimated build time was 18 h 19 min and the volume was 1440 cm^3. With the same additional cost elements, the total print job cost amounted to 2496.91 euros Figure 17 makes the single part cost 208.76 euros. Printing one bracket is 337% more expensive than printing a full layer of parts.

In the next step, we added one more layer of parts in the Z direction to position 24 parts in the build chamber. This 3d nesting generated additional support between the parts. It is doubling the volume of the support that is touching the bed with an exact mirror image. The build time calculated estimate came as 40 h. The total cost estimate was 5243.63 euros Figure 18 and the single par cost amounted to 218.48 euros. That is almost 10 euros additional cost per part. The extra time to build the support between the layers can't be offset by the savings from a scale from the pre and post-processing fees. Mind that we just doubled the number of parts.

For the full-scale 3D nest, we stack 10 layers of parts, a total of 120 to fill the maximum build chamber. The total build time estimate came to 213 h. Using the same cost settings, we calculated a price of 26928.42 euros Figure 19 The price per part is 224.40 euros. That is still increased by approximately 6 euros. The print time per part slightly increases compared to what we see in the double-layer nesting as we have the increased support volume between parts. The actual minimum for the use of support material is touch-base support generation for the single-layer nest. That is in line with the findings of Baumers and Holweg (2019) that in the case of volume manufacture of standard parts with AM traditional economies of scale only apply to a limited extent to the process.

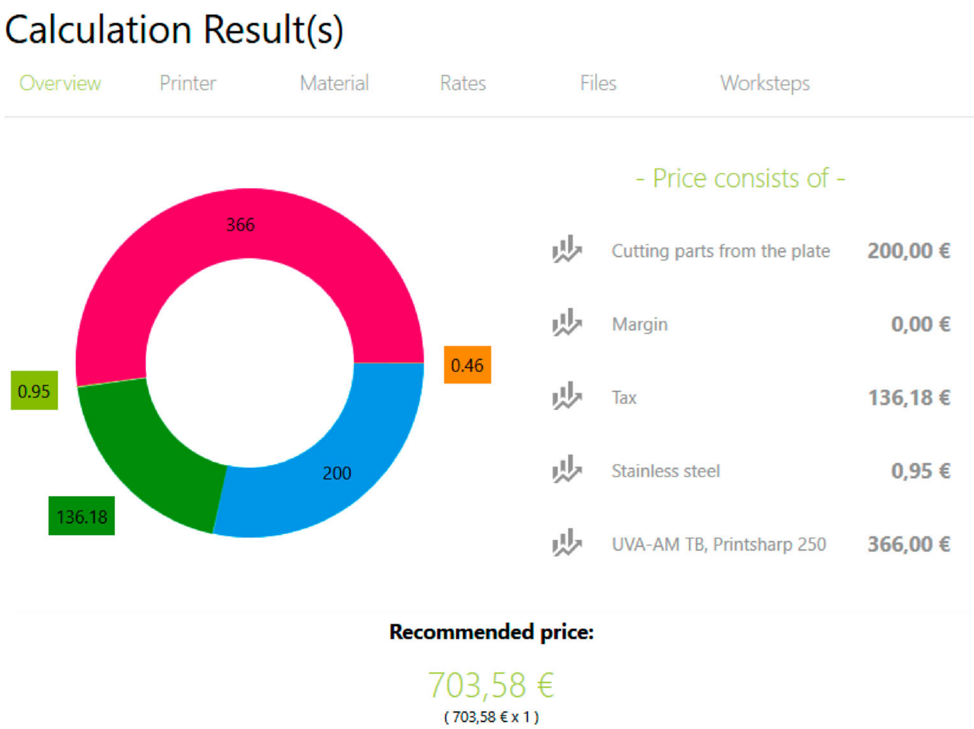


Figure 16. Cost breakdown of single-part pricing.

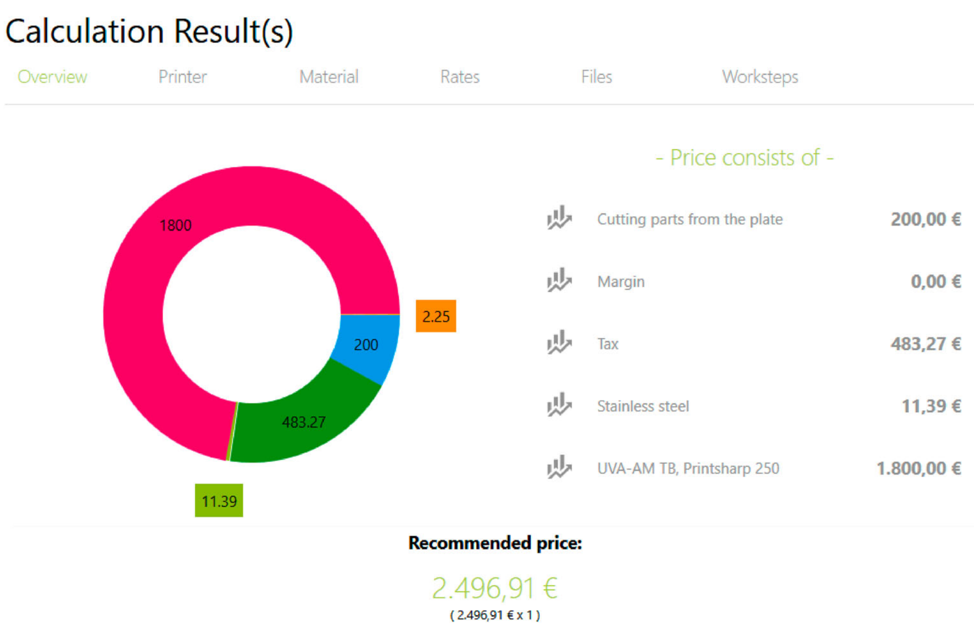


Figure 17. Cost breakdown for 12 parts in a single layer.

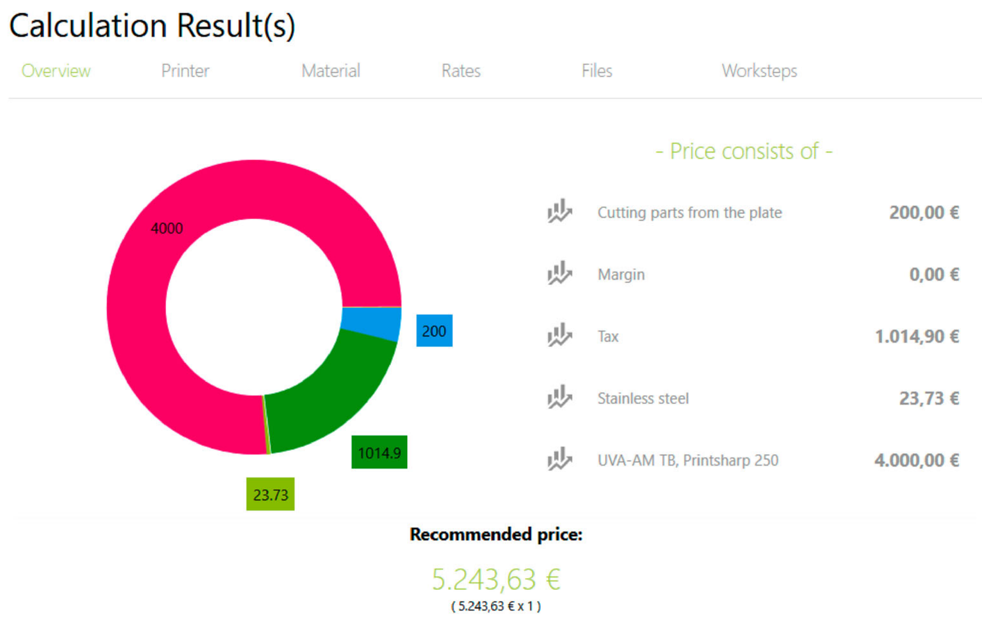


Figure 18. Cost breakdown for 24 parts in two layers.

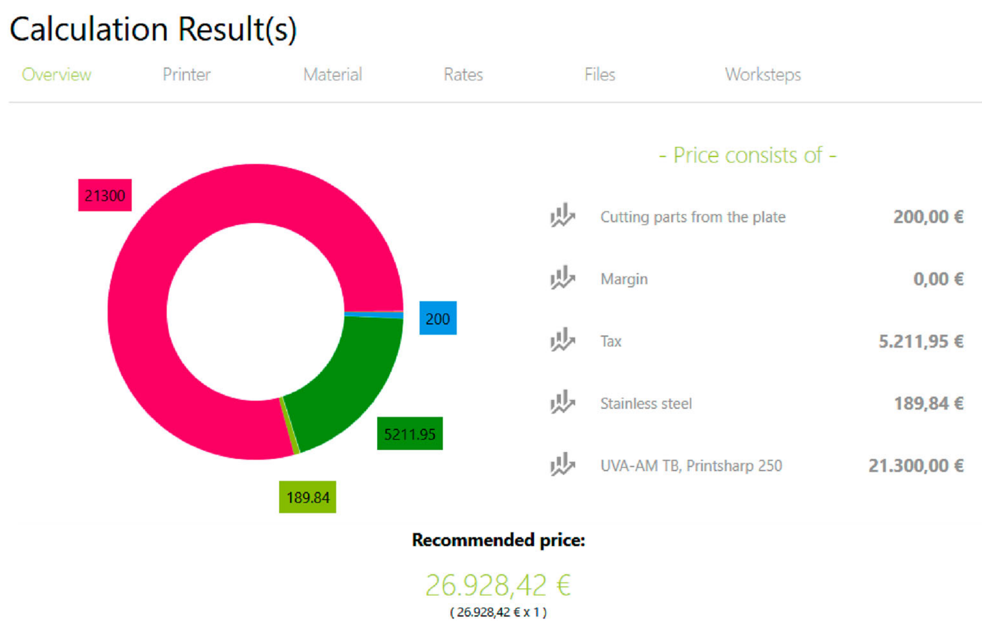


Figure 19. Cost breakdown for 120 parts in ten layers.

5. Advantages and disadvantages of DMLS technology

In the case of conventional manufacturing, there is much more waste, especially in metal production and it is estimated that around 90% of the original raw material ends up as waste on the factory floor. For instance, in the case of milling operation, much of the original raw materials are removed, which creates waste and needs extra cost to remove or manage. In contrast, an AM technology, like DLMS, uses only the necessary raw material for the fabrication of the designed part and its support structure. In some cases need to work a printed object further but even that is significantly less than the milling part (Attaran 2017).

Except for the cost issue, there is also the consideration of the environment. Removing the raw material and making it useable in traditional manufactories requires a lot of energy. The production of this energy most of the time leads to carbon dioxide emissions. There will be a significant issue in the coming years regarding reducing waste of energy consumption in manufactories according to Mosconi 2015 (Mosconi 2015). Small or single product has a very high initial cost with traditional manufacturing, therefore, are profitable only under massive production. The more parts the factory produces, the lower the cost becomes. This is known in the economy as the 'economy of scale' (Dawson 2006). Anderson declares that the AM economy does not change between one million or just one part. In addition, there is no penalty for dealing with just a few parts or making every part unique. AM cannot be compared with traditional manufacturing production when we talk about the massive production of identical product designs.

AM technology offers is the possibility to produce a complex structure of a design that would be very difficult and expensive to produce with traditional manufacturing due to the low demand for parts which means high cost (Lipson and Kurman 2017). Both Lipson and Anderson agree that 3D printing does not offer much to economies of scale and reminds us that this kind of production is profitable only for companies whose strategy is to produce specific products with a defined margin of revenue. Moreover, when a company or business is related to a unique design structure, based on customer needs, would be significantly beneficial for AM and would provide high margins to the company.

The production of a complex design structure has the same cost as the AM process. The cost of producing ten unique parts costs the same as making them customised parts. The production of a decorative ornament has the same cost as printing a plastic simple cube (Anderson 2012). This ability of 3D printing is a great advantage for what we knew as mass customisation. Nowadays many companies offer some customisation to their clients. Every single person has a different attitude and mass body structure which means fully personalised designs and products. 3D printing is a process with no time lean, especially for small batches where AM is more efficient and cost-effective for specific orders. There is no required time for retooling the design product as used to happen in traditional manufacturing. The new product can start printing very quickly after we have finished with the 3D model.

In contrast with traditional manufacturing, we have to run modelling in 3D CAM software for Gcode and adjust the right tool in the CNC machine. All of these systems might seem easy but are not because you have to consider many factors. But with AM this happens easily, on-demand, for every part that we have to print (Lipson and Kurman 2017). Moreover, is by far more flexible and customised as we already said. This means that if the manufacturer wants to make a change to the design part of the product the only thing that is needed is to change the 3D model, instead of changing the entire line production. The 3D machine is the same and the only thing that will change is the 3D model drawing (Anderson 2012).

On the other hand, there are several disadvantages to 3D print technology compared to conventional manufacturing. Even though AM has some clear advantages, especially for small production there are limitations to this process as well. It seems that time, size, volume, material cost, and machine cost are the most common drawbacks. There are some more very important disadvantages: limited material that can be used. Material-wise, only a few of the over 5500 technical alloys available on the market are suitable with metallic AM. In metallic AM, failure (cracking) due to residual pressures generated by solidification shrinkage is a challenge. Although AM offers its own set of advantages, researchers must consider how to overcome its drawbacks. Because of a slower production rate, it would be very difficult to motivate manufacturers of mass-produced items to start moving into 3D printing due to its inherent initial investment cost (Dawson 2006). The actual production time of 3D printing is significantly longer in comparison with a mass-produced manufacturing line, even though it is believed that 3D printing technologies will become faster eventually in the coming years (Barnett 2013).

6. Conclusions

The objective of this research was to redesign and minimise the weight of three parts of an e-scooter, namely neck, platform, and bracket, using TO and Lattice integration in the design, then manufacture the part as a demonstration sample and perform a cost analysis of the effect of 3D nesting strategies on pricing. Full machine volume capacity 3D nesting for DMLS production is represented. The electric scooter generally weighs more due to the mass of its batteries. The range of the scooters is also directly affected, so minimising the mass of the components brings about a performance advantage.

This paper has presented the process of re-designing parts for DLMS 3D printing using the FEM method and TO tools to improve stiffness and reduce mass. Based on this workflow, TO enables optimisation of the structure with higher stiffness and safety factor level, and it can also be deployed to traditional manufacturing with some limitations such as product shape, strength, etc. This study also highlighted that to achieve an efficient workflow it is necessary to deploy more than just one single software. In general, CAD programmes come with a lot of constraints when used for AM-specific optimizations. In this study, the parts of an e-scooter were designed using NX Unigraphics and Altair Inspire software for TO analysis. Altair Inspire was deployed to improve the mass of the three parts through FEA analysis. Design workflow is still not optimal and the engineers need to switch between different software environments and file formats, which makes it difficult. A comparison of the production cost of each part for conventional manufacturing and 3D metal printing showed that TO and lattice integration could reduce material consumption and the weight of the part, and in the case of DLMS, also reduce the cost of the part.

Furthermore, the additional cost analysis of 2D and 3D nesting effects showed how optimising the capacity of Additive Manufacturing machines affects single-part pricing. As the printing workflow includes pre and post-processing steps that are lengthy and expensive, dividing these between maximum amounts of parts for a single print job can reduce cost several times. The biggest price difference came between a single-part print and a fully stacked 2D layer. Further 3D nesting still provides economy of scale, especially when all pre and post-processing costs are accounted for with real production values. For example, initial gas inserting of the build chamber, bed leveling process, first layer calibration, powder loading, and finished parts de-powdering and support removal are done manually and can vary significantly depending on the part geometry, print orientation, operator experience, etc. factors that are difficult to simulate. Still, with full 3D nesting, there is extra support generated between the layers that increase the machine time, the most significant price element. The actual minimum for the use of support material is touch-base support generation for the single-layer nest. That leads to the conclusion that if possible, designers can utilise the part geometry itself to support the next layer. In such a way further process time savings can be made.

In this study, it was noticed that different boundaries and densities through different applied load conditions affect the optimisation results. The designers can utilise the presented optimisation method and consider one single factor at a time such as weight, load, volume, stiffness, safety factor, etc. 3D printing contributes towards true mass customisation with reduced production costs. On the other hand, the initial cost of a 3D metal printing machine and/or infrastructure is still expensive and hardly competes with mass production only on a cost basis. It also takes a long time to fabricate a part through 3D metal printing. For instance, if the company wants to maximise the quantity, then it would require not only a huge number of 3D printers but also a large number of technicians to operate them. Although 3D printing is offering unique manufacturing capabilities designing the business case behind each part requires re-designing using advanced methods like TO and lattice structure integration.

6.1. Suggestions for further research

Further research in this field should include direct collaboration between the TO algorithm and AM. One advanced idea would be to include AM in the TO algorithm and all under the CAD system software. This would not be easy since many constraints should be taken into consideration in both methods. Yet, until these difficulties are left behind, TO will remain a powerful tool that can be used for AM. In the long term will be necessary to understand how 3D geometry changes are connected with the optimisation process. As these two technologies are broadly used, hopefully in the coming future the workflow of TO for AM will simplify the way that designing structural components will become a fully automated process.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

3DHubs. 2019, Oct.10. https://www.3dhubs.com/service/.

Aage, N., E. Andreassen, B. S. Lazarov, and O. Sigmund. 2017. “Giga-voxel Computational Morphogenesis for Structural Design.” *Nature* 550: 84–86. doi:10.1038/nature23911.

Abdulhameed, O., A. Al-Ahmari, W. Ameen, and S. H. Mian. 2019. “Additive Manufacturing: Challenges, Trends, and Applications.” *Advances in Mechanical Engineering* 11 (2): 1–27. doi:10.1177/1687814018822880.

Allaire, G., M. Bihr, and B. Bogosel. 2020. “Support Optimization in Additive Manufacturing for Geometric and Thermo-Mechanical Constraints.” *Structural Multidisciplinery Optimization* 61: 2377–2399. doi:10.1007/s00158-020-02551-1

Anderson, C. 2012. Makers : the new industrial revolution. Retrieved from https://www.worldcat.org/title/makers-the-new-industrial-revolution/oclc/812195098.

Attaran, M. 2017. “Additive Manufacturing: The Most Promising Technology to Alter the Supply Chain and Logistics.” *Journal of Service Science and Management* 10: 189–205. doi:10.4236/jssm.2017.103017

Atzeni, E., L. Iuliano, G. Marchiandi, P. Minetola, A. Salmi, E. Bassoli, L. Denti, and A. Gatto. 2014. Additive manufacturing as a cost-effective way to produce metal parts. *High Value Manufacturing: Advanced Research in Virtual and Rapid Prototyping - Proceedings of the 6th International Conference on Advanced Research and Rapid Prototyping*, VR@P 2013, 3–8. http://www.scopus.com/inward/record.url?eid = 2-s2.0-84892170335&partnerID = 40&md5 = 421b7fb968df54ddbc76a4acba9f87a6.

Awad, A., A. Goyanes, A. W. Basit, A. S. Zidan, C. Xu, W. Li, R. J. Narayan, and R. K. Chen. 2023. "A Review of State-of-the-Art on Enabling Additive Manufacturing Processes for Precision Medicine." *Journal of Manufacturing Science and Engineering* 145 (1): 010802 (21 pages). doi:10.1115/1.4056199

Barba, D., E. Alabort, and R. C. Reed. 2019. "Synthetic Bone: Design by Additive Manufacturing." *Acta Biomaterialia* 97: 637–656. doi:10.1016/j.actbio.2019.07.049

Barnett, C. 2013. 3D Printing: The Next Industrial Revolution. https://www.explainingthefuture.com/3dp_chapter1.pdf.

Baumers, M., and M. Holweg. 2019. "On the Economics of Additive Manufacturing: Experimental Findings." *Journal of Operations Management* 65 (8): 794–809. doi:10.1002/joom.1053

Bendsøe, M. P., and O. Sigmund. 1999. "Material Interpolation Schemes in Topology Optimization." *Archive of Applied Mechanics (Ingenieur Archiv)* 69 (9–10): 635–654. doi:10.1007/s004190050248

Bertolino, G., and M. Montemurro. 2022. "Two-scale Topology Optimisation of Cellular Materials Under Mixed Boundary Conditions." *International Journal of Mechanical Sciences* 216: 106961. doi:10.1016/j.ijmecsci.2021.106961

Cardeal, G., M. Leite, and I. Ribeiro. 2023. "Decision-support Model to Select Spare Parts Suitable for Additive Manufacturing." *Computers in Industry* 144: 103798. doi:10.1016/j.compind.2022.103798

Chen, L., Y. He, Y. Yang, et al. 2017. "The Research Status and Development Trend of Additive Manufacturing Technology." *International Journal of Advanced Manufacturing Technology* 89: 3651–3660. doi:10.1007/s00170-016-9335-4

Conner, B. P., et al. 2014. "Making Sense of 3-D Printing: Creating a Map of Additive Manufacturing Products and Services." *Additive Manufacturing* 1: 64–76. doi:10.1016/j.addma.2014.08.005

Costa, G., M. Montemurro, and J. Pailhès. 2021. "NURBS Hyper-Surfaces for 3D Topology Optimization Problems." *Mechanics of Advanced Materials and Structures* 28 (7): 665–684. doi:10.1080/15376494.2019.1582826

Costa, G., M. Montemurro, J. Pailhès, and N. Perry. 2019. "Maximum Length Scale Requirement in a Topology Optimisation Method Based on NURBS Hyper-Surfaces." *CIRP Annals* 68 (1): 153–156. doi:10.1016/j.cirp.2019.04.048

Costabile, G., M. Fera, F. Fruggiero, A. Lambiase, and D. Pham. 2017. "Cost Models of Additive Manufacturing: A Literature Review." *International Journal of Industrial Engineering Computations* 8 (2): 263–283. doi:10.5267/j.ijiec.2016.9.001

Coykendall, J., M. J. Cotteleer, J. Holdowsky, and M. Mahto. 2014. "3D Opportunity in Aerospace and Defense: Additive Manufacturing Takes Flight." *Deloitte Serial of Additional Manufacturing* 1: 3–6.

Dawson, G. 2006. Economics and Economic Change, Retrieved from https://books.google.fi/books?hl = en&lr = &id = PXVRixnlqRMC&oi = fnd&pg = PR9&dq = Dawson,+G.+Economics+and+Economic+Change&ots = aCK9epMHjR&sig = HL7EGa-edd9VKKk64M7GIG4dADk&redir_esc = y#v = onepage&q = Dawson%2C G. Economics and Economic Change&f = false.

De Jong, J. P., and E. de Bruijn. 2013. "Innovation Lessons from 3-D Printing." *MIT Sloan Management Review* 54: 43–52.

Derakhshanfar, S., R. Mbeleck, K. Xu, X. Zhang, W. Zhong, and M. Xing. 2018. "3D Bioprinting for Biomedical Devices and Tissue Engineering: A Review of Recent Trends and Advances." *Bioactive Materials*, doi:10.1016/j.bioactmat.2017.11.008.

de Siqueira, R. S., I. Mozgova, and R. Lachmayer. 2018. "An Interfacial Zone Evolutionary Optimization Method with Manufacturing Constraints for Hybrid Components." *Journal of Computational Design and Engineering* 6 (3): 387–397. doi:10.1016/j.jcde.2018.10.003

Easter, S., J. Turman, D. Sheffler, et al. 2013. "Using Advanced Manufacturing to Produce Unmanned Aerial Vehicles: A Feasibility Study." In *Proceedings of SPIE Defense, Security, and Sensing*. Baltimore, MD, 22 May, pp. 874204-1–16. Bellingham, WA: SPIE.

Fillingim, K. B., R. O. Nwaeri, C. I. J. Paredis, D. Rosen, and K. Fu. 2020. "Examining the Effect of Design for Additive Manufacturing Rule Presentation on Part Redesign Quality." *Journal of Engineering Design* 0 (0): 1–34. doi:10.1080/09544828.2020.1789569

Gao, W., et al. 2015. "The Status, Challenges, and Future of Additive Manufacturing in Engineering." *Computer-Aided Design* 69: 65–89. doi:10.1016/j.cad.2015.04.001

Gardner, L. 2023. "Metal Additive Manufacturing in Structural Engineering – Review, Advances, Opportunities and Outlook." *Structures* 47: 2178–2193. doi:10.1016/j.istruc.2022.12.039

Gibson, I. 2017. "The Changing Face of Additive Manufacturing." *Journal of Manufacturing Technology Management* 28 (1): 10–17. doi:10.1108/JMTM-12-2016-0182

Gibson, I., D. Rosen, and B. Stucker. 2010. "Additive Manufacturing Technologies. [Electronic Book] : 3d Printing." *Rapid Prototyping and Direct Digital Manufacturing* (3): 498. Retrieved from https://liverpool.idm.oclc.org/login?url = http://search.ebscohost.com/login.aspx?direct = true&db = cat00003a&AN = lvp.b3869087&site = eds-live&scope = site%5Cnhttp://liverpool.idm.oclc.org/login?url = http://link.springer.com/10.1007978-1-4939-2113-3.

Hagedorn, T. J., B. Smith, S. Krishnamurty, and I. Grosse. 2019. "Interoperability of Disparate Engineering Domain Ontologies Using Basic Formal Ontology." *Journal of Engineering Design* 30 (10-12): 625–654. doi:10.1080/09544828.2019.1630805

Huang, X., and Y. M. Xie. 2008. "A new Look at ESO and BESO Optimization Methods." *Structural and Multidisciplinary Optimization* 35 (1): 89–92. doi:10.1007/s00158-007-0140-4

Hwang, D., C. A. Lauff, K. B. Perez, B. A. Camburn, and K. L. Wood. 2020. "Comparing the Impacts of Design Principles for Additive Manufacturing on Student and Experienced Designers." *International Journal of Engineering Education* 36 (6): 1862–1876.

Jahadakbar, A., M. Nematollahi, K. Safaei, P. Bayati, G. Giri, H. Dabbaghi, D. Dean, and M. Elahinia. 2020. "Design, Modeling, Additive Manufacturing, and Polishing of Stiffness-Modulated Porous Nitinol Bone Fixation Plates Followed by Thermomechanical and Composition Analysis." *Metals* 10: 151. doi:10.3390/met10010151

Jia, F., X. Wang, N. Mustafee, and L. Hao. 2016. "Investigating the Feasibility of Supply Chain-Centric Business Models in 3D Chocolate Printing: A Simulation Study." *Technological Forecasting and Social Change* 102: 202–213. doi:10.1016/j.techfore.2015.07.026

Karayel, E., and Y. Bozkurt. 2020. "Additive Manufacturing Method and Different Welding Applications." *Journal of Materials Research and Technology* 9 (5): 11424–11438. doi:10.1016/j.jmrt.2020.08.039

Khajavi, S., J. Partanen, J. Holmström, and J. Tuomi. 2015. "Risk Reduction in new Product Launch: A Hybrid Approach Combining Direct Digital and Tool-Based Manufacturing." *Computers in Industry* 74: 29–42. doi:10.1016/j.compind.2015.08.008

Kumar, M., A. Sharma, U. K. Mohanty, and S. Simhambhatla. 2019. *Additive Manufacturing with Welding*. Kandi Village, India: *Indian Institute of Technology Hyderabad*.

Laverne, F., F. Segonds, N. Anwer, and M. Le Coq. 2015. "Assembly Based Methods to Support Product Innovation in Design for Additive Manufacturing: An Exploratory Case Study." *Journal of Mechanical Design* 137 (12): 121701. doi:10.1115/1.4031589

Li, G., L. Hu, J. Liu, J. Huang, C. Yuan, K. Takaki, and Y. Hu. 2022. "A Review on 3D Printable Food Materials: Types and Development Trends." *International Journal of Food Science+ Technology* 57 (1): 164–172. doi:10.1111/ijfs.15391

Lipson, H., and M. Kurman. 2013. *Fabricated: The New World of 3D Printing*. Indianapolis, Indiana, USA: John Wiley & Sons, Inc.

Lipson, H., and M. Kurman. 2017. Fabricated : The New World of 3D Printing.

Madhavadas, V., D. Srivastava, U. Chadha, S. A. Raj, M. Thariq, H. Sultan, F. S. Shahar, and A. U. M. Shah. 2022. "A Review on Metal Additive Manufacturing for Intricately Shaped Aerospace Components." *CIRP Journal of Manufacturing Science and Technology* 39: 18–36. doi:10.1016/j.cirpj.2022.07.005

Makhesana, M. A., and K. M. Patel. 2023. "Processing of Biomaterials by Additive Manufacturing." In *In Additive Manufacturing Materials and Technologies, Advances in Additive Manufacturing*, edited by A. Kumar, R. K. Mittal, and A. Haleem, 273–279. Elsevier.

Maleki, E., S. Bagherifard, M. Bandini, and M. Guagliano. 2021. "Surface Post-Treatments for Metal Additive Manufacturing: Progress, Challenges, and Opportunities." *Additive Manufacturing* 37: 101619. doi:10.1016/j.addma.2020.101619

Mellor, S., L. Hao, and D. Zhang. 2014. "Additive Manufacturing: A Framework for Implementation." *International Journal of Production Economics* 149: 194–201. doi:10.1016/j.ijpe.2013.07.008

Montemurro, M. 2022. "On the Structural Stiffness Maximisation of Anisotropic Continua Under Inhomogeneous Neumann–Dirichlet Boundary Conditions." *Composite Structures* 287: 115289. doi:10.1016/j.compstruct.2022.115289

Montemurro, M., G. Bertolino, and T. Roiné. 2021. "A General Multi-Scale Topology Optimisation Method for Lightweight Lattice Structures Obtained Through Additive Manufacturing Technology." *Composite Structures* 258: 113360. doi:10.1016/j.compstruct.2020.113360

Montemurro, M., and K. Refai. 2021. "A Topology Optimization Method Based on Non-Uniform Rational Basis Spline Hyper-Surfaces for Heat Conduction Problems." *Symmetry* 13: 888. doi:10.3390/sym13050888

Mosconi, F. 2015. The New European Industrial Policy. https://doi.org/10.4324/9781315761756.

Najafizadeh, N., M. Rajabi, R. Hashemi, and S. Amini. 2021. "A Method and Apparatus for Determination of the Ultrasonic-Assisted Forming Limit Diagram." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 235 (23): 7062–7073. doi:10.1177/09544062211011509

Ngo, T. D., A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui. 2018. "Additive Manufacturing (3D Printing): A Review of Materials, Methods, Applications and Challenges." *Composites Part B: Engineering* 143: 172–196. doi:10.1016/j.compositesb.2018.02.012

Opgenoord, M. M. J., and K. E. Willcox. 2019. "Design for Additive Manufacturing: Cellular Structures in Early-Stage Aerospace Design." *Structural Multidisciplinary Optimization* 60: 411–428. doi:10.1007/s00158-019-02305-8

Pereiraa, T., J. V. Kennedy, and J. Potgieter. 2019. "A Comparison of Traditional Manufacturing vs Additive Manufacturing, the Best Method for the job." *Procedia Manufacturing* 30: 11–18. doi:10.1016/j.promfg.2019.02.003

Portanguen, S., P. Tournayre, J. Sicard, and P.-S. Mirade. 2018. Study and Realization of a 3D Printhead for Meat-based Food. *EFFOST Annual Conference*, Nantes, France.

Prabhu, R., S. R. Miller, T. W. Simpson, and N. A. Meisel. 2020. "Built to win? Exploring the Role of Competitive Environments on Students' Creativity in Design for Additive Manufacturing Tasks." *Journal of Engineering Design* 31 (11-12): 574–604. doi:10.1080/09544828.2020.1851661

Prabhu, R., T. W. Simpson, S. R. Miller, and N. A. Meisel. 2021. "Fresh in My Mind! Investigating the Effects of the Order of Presenting Opportunistic and Restrictive Design for Additive Manufacturing Content on Students' Creativity." *Journal of Engineering Design* 32 (4): 187–212. doi:10.1080/09544828.2021.1876843.

Prabhu, R., T. W. Simpson, S. R. Miller, and N. A. Meisel. 2022. "Mastering Manufacturing: Exploring the Influence of Engineering Designers' Prior Experience When Using Design for Additive Manufacturing." *Journal of Engineering Design* 33 (5): 366–387. doi:10.1080/09544828.2022.2075222

Pradel, P., Z. Zhu, R. Bibb, and J. Moultrie. 2018a. "Investigation of Design for Additive Manufacturing in Professional Design Practice." *Journal of Engineering Design*. doi:10.1080/09544828.2018.1454589.

Pradel, P., Z. Zhu, R. Bibb, and J. Moultrie. 2018b. "A Framework for Mapping Design for Additive Manufacturing Knowledge for Industrial and Product Design." *Journal of Engineering Design* 29 (6): 291–326. doi:10.1080/09544828.2018.1483011.

Praveena, B. A., N. Lokesh, A. Buradi, N. Santhosh, B. L. Praveena, and R. Vignesh. 2022. "A Comprehensive Review of Emerging Additive Manufacturing (3D Printing Technology): Methods, Materials, Applications, Challenges, Trends and Future Potential." *Materials Today: Proceedings* 52 (3): 1309–1313. doi:10.1016/j.matpr.2021.11.059

Rahmatabadi, D., M. Tayyebi, N. Najafizadeh, R. Hashemi, and M. Rajabi. 2021. "The Influence of Post-Annealing and Ultrasonic Vibration on the Formability of Multilayered Al5052/MgAZ31B Composite." *Materials Science and Technology* 37 (1): 78–85. doi:10.1080/02670836.2020.1867784

Roiné, T., M. Montemurro, and J. Pailhès. 2021. "Stress-based Topology Optimization Through non-Uniform Rational Basis Spline Hyper-Surfaces." *Mechanics of Advanced Materials and Structures*, doi:10.1080/15376494.2021.1896822.

Rosenthal, S., F. Maaß, M. Kamaliev, et al. 2020. "Lightweight in Automotive Components by Forming Technology." *Automot. Innovation* 3: 195–209. doi:10.1007/s42154-020-00103-3

Rosenthal, S., S. Platt, R. Hölker-Jäger, et al. 2019. "Forming Properties of Additively Manufactured Monolithic Hastelloy X Sheets." *Materials Science and Engineering, A* 753: 300–316. doi:10.1016/j.msea.2019.03.035

Rouf, S., A. Malik, N. Singh, A. Raina, N. Naveed, M. I. H. Siddiqui, and M. I. U. Haq. 2022. "Additive Manufacturing Technologies: Industrial and Medical Applications." *Sustainable Operations and Computers* 3: 258–274. doi:10.1016/j.susoc.2022.05.001

Salem, H., H. Abouchadi, and K. Elbikri. 2020. "Design for Additive Manufacturing." *Journal of Theoretical and Applied Information Technology* 98 (19): 3043–3054.

Sames, W. J., F. A. List, S. Pannala, R. R. Dehoff, and S. S. Babu. 2016. "The Metallurgy and Processing Science of Metal Additive Manufacturing." *International Materials Review* 61 (5): 315–360. doi:10.1080/09506608.2015.1116649

Scheele, S. C., M. Binks, and P. F. Egan. 2020. Design and Manufacturing of 3D Printed Foods with user Validation. *ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, August 17–19, Virtual, Online.

Schuh, G., G. Bergweiler, K. Lichtenthäler, F. Fiedler, and S. P. Rebollo. 2020. "Topology Optimisation and Metal Based Additive Manufacturing Welding jig Elements." *Procedia CIRP* 93: 62–67. doi:10.1016/j.procir.2020.04.066

Sigmund, O., and K. Maute. 2013. "Topology Optimization Approaches - A Comparative Review." *Structural Multidiscipline Optimisation* 48: 1031–1055. doi:10.1007/s00158-013-0978-6

Son, Y. 1991. "A Cost Estimation Model for Advanced Manufacturing Systems." *The International Journal of Production Research* 29 (3): 441–452. doi:10.1080/00207549108930081

Sonkamble, V., and N. A. Phafat. 2023. "Current Review on Electron Beam Assisted Additive Manufacturing Technology: Recent Trends and Advances in Materials Design." *Discovery of Mechanical Engineering* 2: 1. doi:10.1007/s44245-022-00008-x.

Townsend, S., R. Picelli, B. Stanford, and H. A. Kim. 2018. "Structural Optimization of Platelike Aircraft Wings Under Flutter and Divergence Constraints." *AIAA Journal* 56 (8): 3307–3319. doi:10.2514/1.J056748

Van Dijk, N. P., M. Langelaar, and F. Van Keulen. 2010. "Critical Study of Design Parameterization in Topology Optimization: The Influence of Design Parameterization on Local Minima." In *2nd International Conference on Engineering Optimization*, September 6-9. Lisbon, Portugal.

Weller, C., R. Kleer, and F. T. Piller. 2015. "Economic Implications of 3D Printing: Market Structure Models in Light of Additive Manufacturing Revisited." *International Journal of Production Economics* 164: 43–56. doi:10.1016/j.ijpe.2015.02.020

Wohlers, T. T., and Wohlers Associates. 2013. Wohlers Report 2013 : Additive Manufacturing and 3D Printing State of the Industry : Annual Worldwide Progress Report.

Xie, Y. M., and G. P. Steven. 1993. "Technical Note a Simple Approach To Structural Optimization." *Computers & Structures* 49 (5): 885–896. doi:10.1016/0045-7949(93)90035-C

Xie, Y. M., and G. P. Steven. 1994. "A Simple Approach to Structural Frequency Optimization." *Computers & Structures* 53 (6): 1487–1491. doi:10.1016/0045-7949(94)90414-6

Yan, Y. H., H. Chen, C. Zhang, K. Guo, K. Yang, R. Chen, N. Cheng, et al. 2019. "Vascularized 3D Printed Scaffolds for Promoting Bone Regeneration." *Biomaterials* 190–191: 97–110. doi:10.1016/j.biomaterials.2018.10.033

Yang, X. Y., Y. M. Xei, G. P. Steven, and O. M. Querin. 1999. "Bidirectional Evolutionary Method for Stiffness Optimization." *AIAA Journal* 37 (11): 1483–1488. doi:10.2514/2.626

Zuo, Z. H., Y. M. Xie, and X. Huang. 2009. "Combining Genetic Algorithms with BESO for Topology Optimization." *Structural and Multidisciplinary Optimization* 38 (5): 511–523. doi:10.1007/s00158-008-0297-5