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Sustainability aspects of additive manufacturing: Leveraging resource efficiency via product design optimization and laser powder bed fusion

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1. Introduction

Different industries such as raw material processing and manufacturing consume enormous amounts of natural resources to produce goods for human consumption and, in the process deplete natural resources, creating wastes and emissions. The raw materials industry refers to "the industry that provides various sectors of the national economy with raw materials, fuels, and power" [1]. The manufacturing industry refers to "the industry that processes raw materials". Raw material can be defined as a primary commodity (e.g., crude, ore) or semi-finished goods (e.g., iron, wood) used to produce energy, semi-finished, and finished goods. Released emissions from such a process, often in gaseous form, are sometimes trapped in the Earth's atmosphere consequently contributing to global warming.

Global warming is the long-term heating up of the Earth's climate system because of trapped heat radiation into the atmosphere that is escaping the Earth to the space sphere [2,3]. These gases released in the form of emissions form layers in the atmosphere, making the Earth warmer than the normal levels [2,4]. This phenomenon, called the greenhouse effect, is caused by greenhouse gases (GHGs) including carbon dioxide (CO_2), methane (CH_4), Nitrous oxide (N_2O) and Chlorofluorocarbons (CFCs) [3]. CO_2 is a long-lasting component of GHGs [2,3] and often contributes the most to GHG emissions. CO_2 is caused by human-induced and naturally occurring activities such as farming, deforestation, land use changes, burning fossil fuels, raw material production decomposition and volcanic eruptions [3] manufacturing/production and related industries and value creation processes [5]. The ongoing industrial era is characterized as a "digital transformation era" with new level offerings of virtual processing and managing of entire value chain of products. I4.0 technologies including additive manufacturing (AM), autonomous robots, artificial intelligence (AI), big data, connectivity, digitalization, industrial internet of things (IIoT), machine learning (ML), and simulations are enablers to sustainable practices [6–11]. Digital transformation capabilities, however, are criticized for the need of high energy-intensities during the training or application [8,9,12]. Studies have shown that the use of the internet and supporting digital tools contribute to GHG (3.7 %) in performing tasks [9,13]. Continuous advancements in research are ongoing to improve these aspects of digitalization [9].

AM, also known as 3D printing, is unabatedly a disruptive manufacturing method, enabling new ways to manufacture unique features of products designs [14]. AM however still has several challenges, such as higher rates of errors and failures. Finding and mitigating such challenges requires a systematic approach by focusing on the First Time Right (FTR) approach for critical applications like aerospace. FTR is defined as a *design process where every activity is performed in a right manner the first time for right requirements at*

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every time [15]. Achieving FTR requires reduction of errors, defects, and rework, which consequentially minimize manufacturing costs, improve product quality, and increase productivity. An example to achieve this goal in manufacturing sector is via simulation assisted designing that equip engineers the ability to virtually simulate, test designs, performances and plan production prior actual manufacturing. Simulations serve as a powerful tool for testing and optimizing designs before they are put into production [16,17] thus are becoming increasingly valuable tools in research and manufacturing [18]. Digitalization and simulations allow engineers to virtually optimize product designs models, and test performance under a wide range of conditions, such as varying loads, pressure, and temperatures [19,20]. In addition to design optimization, simulations can also optimize the manufacturing process [21]. Simulations can be used to optimize production processes in AM, to reduce defects and improve product quality [18]. Simulations can be used to evaluate new product designs, test parts under real life conditions, to identify and rectify problems with intended build plan. This can help identify potential problems and weaknesses in the design, allowing adjustments prior manufacturing [22]. Design and manufacturing engineers via simulations can achieve FTR production, minimize manufacturing time and defects involved in physical prototyping and testing, while also improving the quality, reliability, and safety of products.

This triad of digitalization, simulations and AM, are helping to drive innovation and improve competitiveness in modern manufacturing with sustainable product designs. Simulation-assisted AM can help achieve aspects of sustainable manufacturing (SM) practice with optimized and better performing FTR products [23]. Design optimization can be described as the process of optimizing geometrical structures of a product to improve its function, performance, and efficiency. It involves using mathematical algorithms to find optimal solution among design options (e.g., topology, lattices and honeycomb) to design problems [24]. Generative designs via computing swiftly create design iterations capable of achieving resource efficiency [17,25–27]. Simulation-assisted designs for AM inherently offer means to sustainable production, particularly with the digital layer-by-layer building of products and the elimination of excess material and unnecessary scrap. Powder bed fusion (PBF), a type of AM, can manufacture optimized intricate metal parts [28] not possible via conventional manufacturing (CM) methods [14]. Optimized intricate designs can achieve sustainable target (e.g., better resource consumption, time savings, cost competitiveness, waste, and emissions minimization). There is lack of literature respective to data for comparing the commonly used structural optimization methods (topology, honeycomb, and lattice) in the stance of sustainability. This study is carried out as literature review and virtual design analysis from the perspective of cost functions (time and build volume), and performance functions (structural performance) of additively manufactured metal parts towards resource efficiency.

1.1. *Sustainability and its fundamental enablers*

Sustainability is defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs.” Often considered as environmentalism, sustainability has three equally embedded elements, also referred to as the three pillars of sustainability, namely, environment, economic and social. The environmental pillar of sustainability mostly seeks to maintain ecological integrity. The aspects of environment sustainability entail protecting the ecosystem via sustainable and responsible consumption rate enabling the earth to replenish itself. The economic pillar of sustainability mostly seeks that human communities have access to required resources to meet and maintain their needs. This dimension is concerned with security systems and equal availability to available livelihood sources. Social sustainability mostly seeks the attainment and maintenance of human rights and necessities. Social equity, as commonly termed, is concerned with equal access to adequate resources capable of keeping a healthy and secure society. The concept of sustainability continuously evolves e.g., from the intersecting mode to an integrated model of the three pillars signifying different dimensions of sustainability. Fig. 1a and b represents the core components of sustainability, Fig. 1a shows the intersection and Fig. 1b shows the integration representations of sustainability.

Fig. 1 represents comparable models of true sustainability, denoted by E^3. The integration model depicts that environmental protection leads to the safety of people, products, and communities to make profits. The integrated model can be interpreted to mean

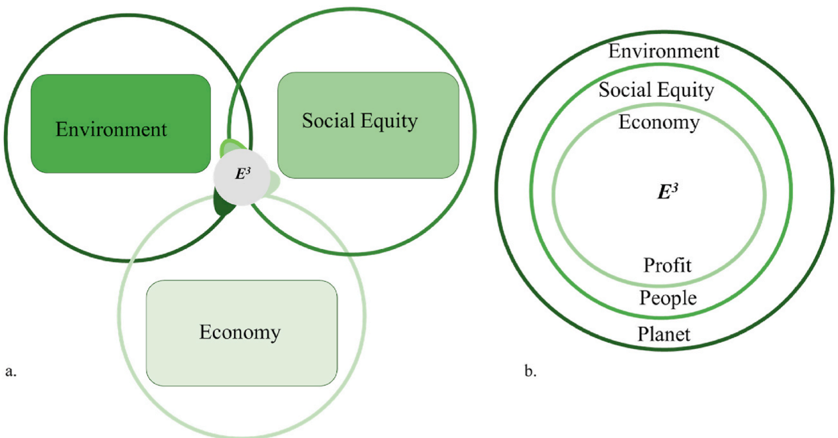


Fig. 1. Representation of the a. intersecting classical model, b. contemporary concentric model of sustainability [29–31].

that the environmental (planet) is the most contributing aspect of sustainability that encompasses the social equity (people) and the economy (profit). All three aspects of sustainability must be satisfied to achieve E^3 irrespective of notion.

The United Nations (UN) in 2015 adopted the 2030 Agenda for its member States anchored by seventeen sustainable development goals (SDGs). The SDGs provide a shared blueprint for member states towards achieving a more sustainable future by 2030 around the areas of people, planet, prosperity, peace and partnership [32]. The SDGs aim to create a better and more livable planet via several social and environmental targets [33]. Some aspects of the SDGs seek to create economic productivity through diversification, productive activities, creativity, and innovative systems [34]. Whereas other target aspects seek efficient use of resources by creating new materials, renewable energies, energy-efficient processes, technological upgrades, and innovations [4,34–37]. Optimizing energy use, raw material consumption, and raw material circularity are exemplary ways to achieving the goal to reduce about 80–95 % of GHG emissions of 1990 levels by 2050 [38,39].

New systems, processes, materials, and relationships are required to facilitate the realization of E^3 to creating and maintaining livable communities for the present and future generations [6,30]. Technologies that use renewable energy sources or produce fewer emissions must be preferred. Applying processes that minimize raw material consumption, waste and emissions will enhance material efficiency via responsible exploiting of natural resources to decrease supply risks. Material efficiency measures the quantity of functional components produced and waste per unit of input material. Efficient use of raw materials is a significant prospect to indirectly mitigate GHG emissions. Optimal product design is one of the ways by which energy efficiency can be achieved. Lightweighting and downsizing of components during the design phase can reduce start-up material, part weight, scrap material and manufacturing time. Extending the lifetime of products through repair, reusing, remanufacturing, refurnishing (post-consumer use), recycling and recovery for raw material and energy after their useful life. Such practices also offset waste materials, reducing the amount of virgin raw material and energy that would otherwise be needed for new parts [39–41].

Manufacturing methods capable of reducing waste, reducing process liquids, improving material utilization through reusing raw material, downsizing, and recycling manufacturing waste are potential processes to achieve SM goals. SM practices have and continue to create balance between the environment, the economy and society [33,42]. The discovery of innovative sustainable practices can create new market opportunities for increased economic competition and growth [42,43]. The adherence to regulatory constraints and identifying new market opportunities are seamlessly associated with SM [44]. Manufacturing industries often use large volumes of raw material and energy to make goods and in the process also create wastes and pollutants [45]. According to Salonitis & Ball [46], manufacturing processes are defined as "the processes that transform materials and information into goods for the satisfaction of human needs". Pollutants are either emitted from the manufacturing process or from secondary systems such as the energy used to produce raw material and for operating the manufacturing machines. The major environmental concerns notably arise from natural resources consumption and created pollutants. Modern manufacturing tends to implement sustainability as an essential tool for effective solutions to tackle these concerns [47] and to provide a competitive edge [48]. SM emphasizes product design that contributes the least negative environmental impact via efficient resource consumption, waste reduction and long-term cycle usage goals utilizing economically sound processes.

Sustainable development (SD) and SM have necessitated an alteration of operational focus to sustainable practices, leading several industry and academic institutions to focus on eco-socio sustainability productions. A few research efforts have investigated SM respective to offered sustainable practices [49–51]. SM practices boost processes and products that protect ecosystem services, reduce ecosystem degradation, and rehabilitate degraded environments. Such practices include designing optimized products, emission-free processes that enhance responsible consumption, performance efficiencies, and reduced negative ecologic, financial, and health-related impacts. Companies adopting such sustainable practices can benefit from gaining the trust of employees and customers [52,53]. The safety of personnel and the community can be enhanced through socio-environmentally sound methods of adhering to SM principles. Several industries continue to develop and adopt innovative approaches including lightweighting and digitalization towards SDGs achievement. Digitalization is the use of digital tools for the representations of design, evaluation, and management of product or process life cycle along a digital thread. Digital thread fosters better interoperability between software and hardware for traceability and management of all design data, product data and supply chain data that are used to create products. Modern digital tools offer powerful and effective routes to create optimized and lightweight products to replace conventional bulky parts. Optimized downsized and lightweight parts are means to minimize raw materials consumption and manufacturing time. Lightweighted parts offer benefits during the use phase, such as enhanced fuel economy, better functionality, reduced waste, and emissions [54]. Utilizing lightweighting for dynamic application products such as transportation helps improve operational performance, achieve better fuel efficiency, cost-effectiveness, reduced waste and controlled GHG emissions [55,56]. Lightweight components used in cars and airplanes improve performance and energy efficiency during the use phase [57–60].

AM contributes to the SDGs, for instance, integrating AM machine systems different I4.0 elements such as AI, autonomous, robots, connectivity, digitalization, IIoT, ML and simulation can perform routine tasks in modern industries [12,59]. Potentially such integration adds value, decreases energy consumption, raw material consumption, minimizes waste and emissions [5,7,8,61] and reduced human fatique and errors. Inputs and outputs can be controlled seamlessly to create opportunities that improve efficiency, reduce lead-times [59,62], increase outputs, reduce errors, enhance cost savings and customer satisfaction [12,62]. The capabilities of simulations and digital tools ease the identification of problems and strengthen existing solutions or create new set of solutions for achieving different sustainable goals. Swifter decision-making is possible through data-driven and simulation-assisted processing, monitoring, managing and resource usage [9,63]. Unpredictable and vast data can easily be identified to support and strengthen social safety within networks via the application of big data analytics and ML [28,42,64]. The interoperability and autonomous nature of digital tools provide means to increase quality, reliability, and production speed void of human-induced errors [25,65,66]. For instance, simulation tools and design for additive manufacturing (DfAM) rules can aid in designing and manufacturing efficient parts in consideration of AM specific constraints void of preventable errors. Industrial machinery equipped with AI and autonomous systems allows machines to sense and navigate their environment to effectively and autonomously communicate to perform functions [10,67,68]. The advantages of such autonomous AM machine systems include reduced faulty build cycles and energy efficiencies [64,69], reduced resource consumption, time usage, and overall production costs [70–72]. Utilizing computer-based software and automated controlling systems can reduce manufacturing waiting times.

1.2. Aims, motivation and methods

This study aims to add to sustainability aspects of AM through reviewing of performance indicators used to achieve manufacturing efficiencies. The study also aims to highlight some of the inherent AM sustainability stance (e.g., build time, raw material) in pursuit of resource efficiency with a virtual case study of design and manufacturing planning. The motivation is to add to knowledge of simulations-assisted tool prospects in AM towards design optimization and sustainability enhancement. This research is important as it demonstrates how industry 4.0 elements including AM, digitalization and simulations effectively create optimized product designs suiting varying and specific application requirements which also are vital to SM. SM may be defined as the production of goods through economically sound, safe methods, efficient energy systems that boosts natural resource conservation, and minimizes harmful environmental impacts.

This study consists of two sections; a literature review conducted via SCOPUS database, and a virtual cantilever design optimization case. The former considers the influence of computer modelling and simulation in AM for product design and its contribution to enhancing SM. The goal was to explore FTR optimized products via simulation-assisted designing for AM for improving sustainability (e.g., functions, resource efficiency). The latter investigates influences of three types of design optimization methods, namely, *topology, honeycomb, and lattices* in relation to part weight and build time based on laser powder bed fusion (L-PBF). This subcategory of PBF uses the energy of laser beam to successively melt and fuse pre-determined exposed powder layers on a powder bed. The aim of the design case was to identify how the design optimization methods via computer modelling and simulation affects performance and resource efficiency. The experimental study considered only virtual design and manufacturing planning with a simple loading case of a 100 N pivoted cantilever. The study via simulations evaluated the possibilities of part design optimization on build weights and times as these directly impact on production efficiencies (e.g., raw material usage, energy consumption and costs).

2. Literature review

AM offers enormous benefits to the ongoing sustainable quest, however, there is still lack of knowledge on its effective implementation to enhancing sustainability. The utilization of AM with the right simulation tools and design guidelines has the potential to influence SM goals. This review gives an overview of key concepts including metal AM and product design optimization respective to sustainability, SD and SM.

2.1. Trends in additive manufacturing sustainability studies

The review aimed to investigate and understand the current study trend regarding sustainability aspects of AM. The aim was to identify determinants of sustainability in existing AM sustainability related studies of the past and current trends. Identified determinants were examined for an in-depth knowledge and understanding of their leverages to sustainability. The aim was to find the underexplored topics as basis for current and future studies. The literature review was guided by two main research questions (RQ) as follows.

1. RQ1: How has research in AM sustainability evolved over the last decade?

This question was answered with a bibliographic study on the general trends of AM sustainability aspects. The review also considered the aspects of design optimization and simulations regarding AM sustainability. Preliminary search hits for "computer-based design", "simulation" and "digitalization" in relation to product design optimization in AM were categorized in themes of sustainability. The paired sustainability themes included green manufacturing and sustainable manufacturing as sometimes used in literature to discuss manufacturing sustainability aspects [11,73,74].

2. RQ2: How does AM contribute to SM targets for metal production from the aspect of function, costs, and resource efficiency?

This question was answered with a detailed evaluation of the most closely related publications on metal AM sustainability with respect to design optimization.

This review was carried out using SCOPUS and primarily using keywords and Boolean operators considering six document types: research articles, review articles, conference articles, conference reviews, books, and book chapters in English. Different keywords on themes of AM and sustainability, including 3D printing, powder bed fusion, design optimization, circular economy, green manufacturing, and sustainable development were initially used to identify suitable introductory literature. The initial search string (SS0) used to locate introductory studies of keywords were paired to identify, firstly AM sustainability aspects, and secondly, specific studies with focus on design optimization contribution to AM sustainability. The review carried out in this study was limited to 2012–2023 in agreement with AM sustainability aspects. The initial search was performed in April 2022 and updated in June 2023 to capture current state-of-the-art in the interval of manuscript submission timeline. The used Boolean operators (SS1) "additive manufacturing" OR "3D printing" AND "sustainability", (SS2) "additive manufacturing" OR "3D printing" AND "green manufacturing", and (SS3) "additive manufacturing" OR "3D printing" AND "sustainable development" respectively yielded 1308, 163, and 903 hits respectively.

Fig. 2 and Table 1 respectively show the total located number of publications and number of yearly publications per search string. Research on sustainability aspects of AM have. There result show an increase in research for all the topics considered, generally post the UN SDGs introduction in 2015. This growth is expected to continue as AM becomes part of mainstream manufacturing and educational curriculum.

The second set of Boolean operators, SS4, SS5, SS6, and SS7 used identify, screen, and evaluate for eligibility and inclusion correlated to AM sustainability from the perspective of simulation and product design optimization. The search string combined keywords such as simulation, computer-aided design, design optimization, topology optimization, as well as SS1, SS2 AND SS3. The Boolean operators used were: (SS4) "simulation" AND "design optimization AND "additive manufacturing" OR "3D printing" – which gave 139 hits, (SS5) "computer-aided design" AND "design optimization" AND "additive manufacturing" OR "3D printing" – which gave 69 hits, (SS6) "simulation" OR "design optimization" AND "additive manufacturing" OR "3D printing" AND "sustainability" – which gave 85 hits, and (SS7) "simulation" OR "design optimization" OR "topology optimization" AND "additive manufacturing" OR "3D printing" AND "sustainability" AND "metal" – which gave 18 hits. Fig. 3 and Table 2 summarize key study trends with SS4, SS5, SS6 AND SS7.

Fig. 3 and Table 2 respectively show the total number of publications and yearly records. The bibliographic study outcome illustrates growth of AM sustainability research from design optimization perspective. A final deciding search string, SS7, was used to limit the retrieved studies to include metal AM studies only in agreement with this study. The authors selected the most relatable literature following a full-text screening of abstracts and keywords of the retrieved 18 articles. A total of 14 relevant publications including [16,40,41,50,58,75–83], were selected, from journal articles, conference proceedings and book chapters which focused on the effects of design optimization on metal AM sustainability aspects. Fig. 4 summarizes the identified key leverages of metal AM towards sustainability by the fourteen articles.

As Fig. 4 illustrates the commonly identified leverages of sustainability aspects in AM. For example, Qu et al. [83] showed how energy efficiency can be enhanced for laser metal AM and open opportunities to new material development for further energy efficiency improvements. Cingolani et al. [16] performed simulation and printed material that enhanced the strength, recyclability, cleanliness, and environmental sustainability of sound absorbers in a lecture hall, relating to the requirements after COVID-19. DeBoer et al. [82] in a comparative life cycle assessment study for AM and CM methods showed that PBF powered with renewable energy offered the best environment-friendliness route for metal components. Aziz et al. [41] in a study showed how AM through AI capabilities supports remanufacturing (repair and restoration) in support of raw material efficiency, improved product performance, functionality and extension of service life. AM is highlighted to enhance smart, sustainable and cost-effective manufacturing route in achieving SDGs 3, 4, 7, 8, 9,11, and 12.

3. Metal additive manufacturing

The International Organization for Standardization (ISO/ASTM 52900-2021) defines AM as "the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [84]. There are seven categories of AM including.

1. Powder bed fusion (PBF): an AM "process in which thermal energy selectively fuses regions of a powder bed"
2. Binder jetting (BJT): an AM "process in which a liquid bonding agent is selectively deposited to join powder materials"
3. Material jetting (MJT): an AM "process in which droplets of build material are selectively deposited"
4. Directed energy deposition (DED): an AM "process in which focused thermal energy is used to fuse materials by melting as they are being deposited"

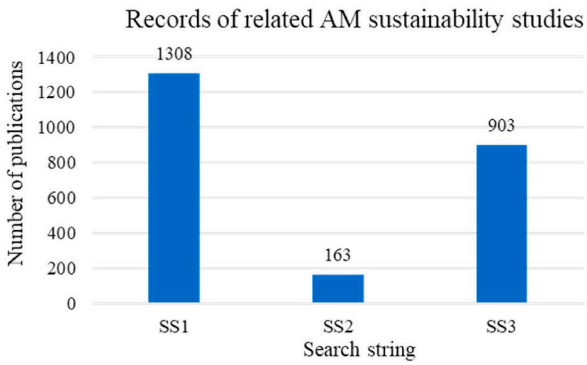


Fig. 2. Representation of the total number of publications per year from bibliographic study.

Table 1
Yearly identified records on AM sustainability aspects.

Search string Year	SS1	SS2	SS3
Number of publications			
2012	0	1	0
2013	11	0	3
2014	17	2	14
2015	25	5	23
2016	42	1	36
2017	71	4	74
2018	90	8	56
2019	110	13	104
2020	158	61	96
2021	244	49	160
2022	324	15	195
2023 (to June)	216	4	142
Total	1308	163	903

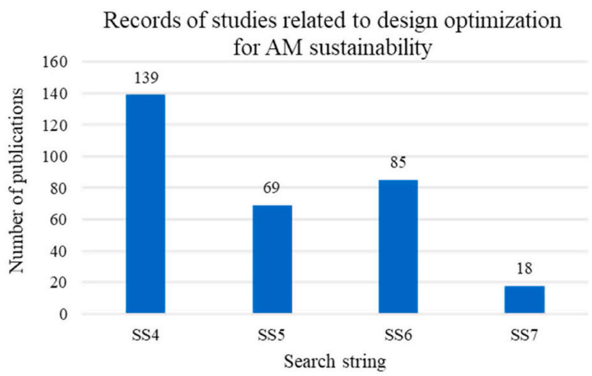


Fig. 3. Representation of total number of publications per year from bibliographic study.

Table 2
Yearly records for AM design optimization sustainability aspects.

Search string Year	SS4	SS5	SS6	SS7
Number of publications				
2012	0	0	0	0
2013	1	0	1	0
2014	0	3	3	2
2015	5	3	2	0
2016	3	4	4	0
2017	12	10	6	0
2018	11	6	2	0
2019	13	8	4	1
2020	20	10	10	1
2021	23	11	20	7
2022	38	9	20	4
2023 (to June)	13	5	13	3
Total	139	69	85	18

5. Material extrusion (MEX): is an AM “process in which material is selectively dispensed through a nozzle or orifice”
6. Sheet lamination (SHL): an AM “process in which sheets of material are bonded to form a part”
7. Vat photopolymerization (VPP): an AM “process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization” [84].

The various AM categories differ in terms of technological principles, process layout, part resolution, need for a vacuum in the chamber, melting or bonding mechanism, component size, form and type of materials [85–87]. The different categories, however, begin and end in a similarly sequential manner. The main stages of AM may be classified into digital, physical manufacturing, and

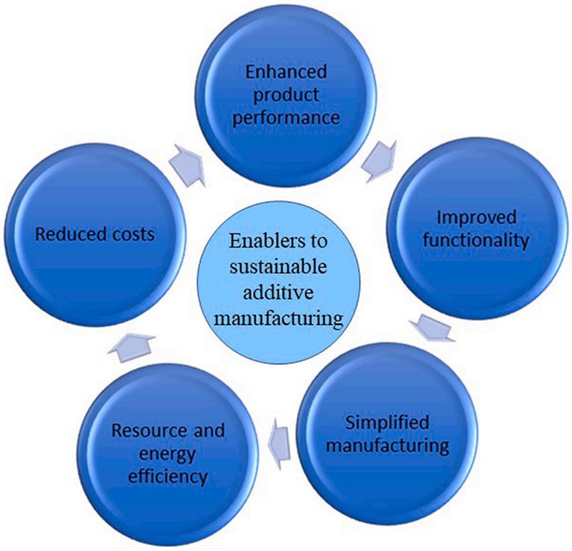


Fig. 4. Key identified metal AM leverages for enhancing sustainability aspects from the most relevant studies.

post-processing. The digital stage includes the idea generation, scanning for or computer-aided design (CAD) modelling of the three-dimensional (3D) model; the slicing of the 3D model into two-dimensional (2D) layers (STL format) and generating of the AM machine readable G-codes needed to print the components on a machine [59,87]. Physical manufacturing consists of machine set-up, process parameters selection, part orientation, nesting, support generation and the layer-by-layer printing of the different layers into physical parts. Post-processing follows through CM methods, which is done to improve the properties of the as-build parts. Post-processing is often mandatory through example cutting, heat treatment, machining and polishing [88,89]. Post-processing is required to separate the as build part from build plate and to obtain improvements such as surface quality, mechanical properties, dimensional accuracy, densification, etc., according to the expected properties and application requirements.

AM can manufacture a variety of shapes (low to high complexity) and forms (liquid, sheet, powder, wire) [90–92] in variety of materials such as metals, ceramics, paper [93], polymers and polymer composites [92,94]. Unique nanomaterials, biomaterials and functional materials (e.g., magnetic materials) suitable for AM continue to emerge, potentially broadening area of application [95–99]. The possibility to use multiple materials (multi-material AM) for a component can be used to achieve multi functionality, gradient functionality, and cost-effectiveness [97,100]. Multi-material parts define components comprising of more than one material, for example, fiber reinforced thermoplastic composites, metal-metal, and metal-ceramic [94,97,101].

AM, as an element of I4.0, offers new manufacturing routes capable of enhancing ecological safeguarding and improving economic competitiveness [6,102]. AM enables on-demand and localized manufacturing consequent to time saving, eliminating physical spare parts inventory, minimizing storage area, decreasing transportation needs and reducing CO_2 footprints. AM is transformative due to the ways goods and services are processed and delivered [103–106]. AM can enhance energy efficiency, raw material efficiency, life cycle cost savings, and minimize wastes and emissions [103,107–109]. Nyamekye [110] developed a model for enabling resource efficiencies for better costs via simulations and AM [110]. The model shows how simulation-assisted DfAM can be used to control activities in both design and build phases. The model includes a detailed product design relating to simulation-assisted DfAM in controlling the overall costs.

The adoption of AM has and continues to revolutionize supply chains and operations within different industrial sectors [108, 111–113]. AM comparatively offers operational benefits such as mass customization, localized manufacturing, and ease of adaptability compared to CM [92,103,114,115]. Several studies have classified AM as one of the key drivers along the manufacturing value chain for creating intelligent products and services [106,109,116]. AM uses computer information in a layer-by-layer manner, using the exact quantity of materials to make components using the assistance of a heat source or an adhesive. AM offers several benefits, including design flexibility, lightweighting and customization [117] for improved functionality and better application cost efficiency. The method potentially offers reduced raw material and energy consumptions at different life-cycle phases and reduces lead times evident in the aftersales service. AM can be used to build internal cooling path just below products surfaces, for example mold tools. This offers uniform and rapid cooling and lowers the cycle time during the use phase of components requiring such features. AM also allows hybrid manufacturing (e.g., multi-functional, multi-material and multi-structural) processing [118] which are otherwise not achievable via comparable CM methods. Integrating functional materials and AM can viably create high-value components that require lightweight and novel designs capable of leveraging environmental, economic, and social sustainability benefits [119–121]. AM can also create optimized, individualized, intricate, and superior parts capable of improving functionality, and productiveness [67, 104,122–124]. The use phase of such optimized components offers better energy efficiency and reduced emissions. The manufacturing phase of AM can result in flexibilities, raw material efficiency and reduced negative emission releases [123,125,126].

Energy consumption remains a concern during the actual part building in AM due to the likelihood of high energy intensities [127].

This limitation of AM can be minimized through simultaneous build of multiple similar or dissimilar parts (commonly referred as combined build) to optimize energy consumption [128]. Monitoring and measuring input/output energy and mass flows can also help identify hotspots that can be targeted to control such undesirable energy intensities. Monitoring processes, measuring performance, simulations, certification, and qualification in AM is deemed to explicate the offered benefits in quest to promote a wider adoption [129].

3.1. Product design process

The design process is an approach used to break down a large project into easily workable parts. The design of products is described as an iterative process that connects different hierarchical aspects to select the best solution to a problem via optimization [27]. Product designing is either driven by the process (process-driven) or the designer (designer-driven). A particular functional parameter referred to as the apex (core) can dominate and drive the decisions and actions in the design process that affects the other elements of an individual design sphere. Choices in one process stage can determine the choice in another [130]. The iteration of potential solutions can be analyzed based on experience, intuition or mathematical analysis during the component design process to select the best solution to the design problem [131]. The designing of components can be visualized as an interrelated process that connects the system definition process, component design process, manufacturing planning and quality assurance (QA) illustrated in Fig. 5.

As Fig. 5 shows, the design process needs to (1) define the systems, (2) design the components and (3) plan manufacturing systems as cohesive processes to maximize benefits. When narrowed down to metal AM, all these elements require specified activities for fulfilling the expected design objectives. The system design process investigates the objectives of a component and considers the context in which the component will function. The system definition encompasses aspects such as component selection concerning functional requirements, functional conditions, and its relationship to other components as an element of a larger component. The part design process involves the actual modelling of a component structure based on various expected features in relation to other elements. Using sketches to document ideas can help keep track of concepts throughout the detailed design phase of making CAD designs. Optimization tools and computer-aided tools allow virtual analysis of feasible design iterations and their validation using for instance applied loads, forces, constraints and working conditions [124,132,133] through simplified iterations. Topology, lattice and honeycomb structures are viable using these tools to optimize products design for achieving customization, functional integration, light weighting, and/or downsizing. Manufacturing planning identifies and plans the various manufacturing and QA steps. The manufacturing steps include planning the actual layer-by-layer building of the part and post-processing. For example, selecting optimized process parameter values, type of post-processing method and set-up based on intended application requirement. Part placement or packing considers the build cycle setup including number of parts, orientation and support structures capable of obtaining efficient machine volume utilization, optimizing raw material consumption, effective manufacturing time and other process efficiencies [134,135].

The right use of DfAM rules and digital tools for product designing and the actual build in AM can enhance manufacturing flexibility and resource efficiency. Simulation-assisted DfAM enables a transition to new digital sustainability by improving efficiency, effectiveness, and efficacy via responsible use of production resources. Computer-based software performs vast iterations to create optimized designs and ease manufacturing complexities. The use of simulation-assisted DfAM to create optimized and lightweight metal components directly reduces raw material usage, time, and wastage in the supply chain. For instance, reducing manufacturing time decreases the total energy consumption (which is a product of time and power) and production costs. Thus, any reduction on time directly decreases energy consumption and other time related costs. Fig. 6 shows exemplary contributions to sustainability aspects in

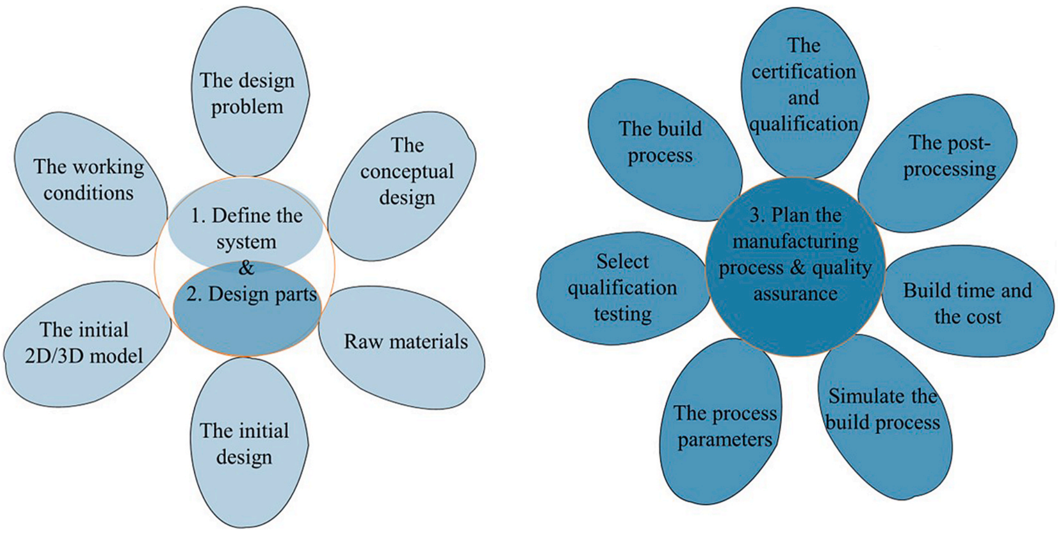


Fig. 5. Representation of a schematic and stepwise model for product designing in AM, redrawn from [110].

AM along the digital thread and simulation-assisted DfAM.

Evident environmental and economic benefits through design optimization are improved performance, durable products, better resource consumptions, and swift manufacturing. Social efficiency is attainable with equal accessibility, effortless application, decentralization, and AM-specific enabling factors via digital thread. The benefits such as the possibility of improved wellbeing, new research field and co-creation are other presumed AM potentials toward social sustainability.

Table 3 is a tabulation of commonly used digital tools along the workflow in AM.

The interoperability of the digital tools listed in Table 3 facilitates a digital thread that promotes agile manufacturing systems throughout life cycle [111].

3.2. Design optimization

A product design optimization concerns the structural optimization, consisting of the size optimization process, the shape optimization or configuration optimization, and the topology optimization [149,150]. Optimizing the structural configuration of products, for example in AM, is vital to achieving the required manufacturability and product quality [126]. Distinctive design optimization methods may is used as single or in combination for various applications, such as aerospace, automotive, and medicine to achieve varying functionality and effectiveness [149]. Studies [24,150–156] discuss structural optimization methods (topology, honeycomb, lattice) and their configuration. Topology optimization method uses mathematical algorithms to optimize structural layout for achieving certain performance or objective function [24]. The method involves removing or adding material to a design space that conforms to specified loads and constraints [14,157]. Topology optimization can be used to create complex structures with required stiffness suitable for different functions without increasing weight [158]. Topology optimization can be achieved with ML models or computational analysis [27]. Lattice optimization is a type of topology optimization where the design is optimized using a lattice structure [24,154]. Lattice structures are regular arrangements of beams or struts that form a repeating pattern to create a variety of lattice structures in regular or non-regular (hierarchy) layout [24,158]. Lattices structures are lightweight and have high strength-to-weight ratios, making them suitable for challenging structural applications requiring both lightweight and stiffness [156,159]. While the former require mass reduction, the latter require mass increment, an engineering challenge that can be solved via topology of the unit cells to achieve gradient lattice structure [158,159]. Lattice structures mimic nature inspired geometries, thus designers through lattices can achieve biomimicry structures for applications where bio-functionality is a critical requirement [156]. Honeycomb optimization is another type of topology optimization that utilizes honeycomb structures consisting example of interconnected hexagonal, triangular or square cells [153] capable of creating strong lightweight yet stiff and strong structures. This type of optimization is commonly used in aerospace, where weight reduction is critical.

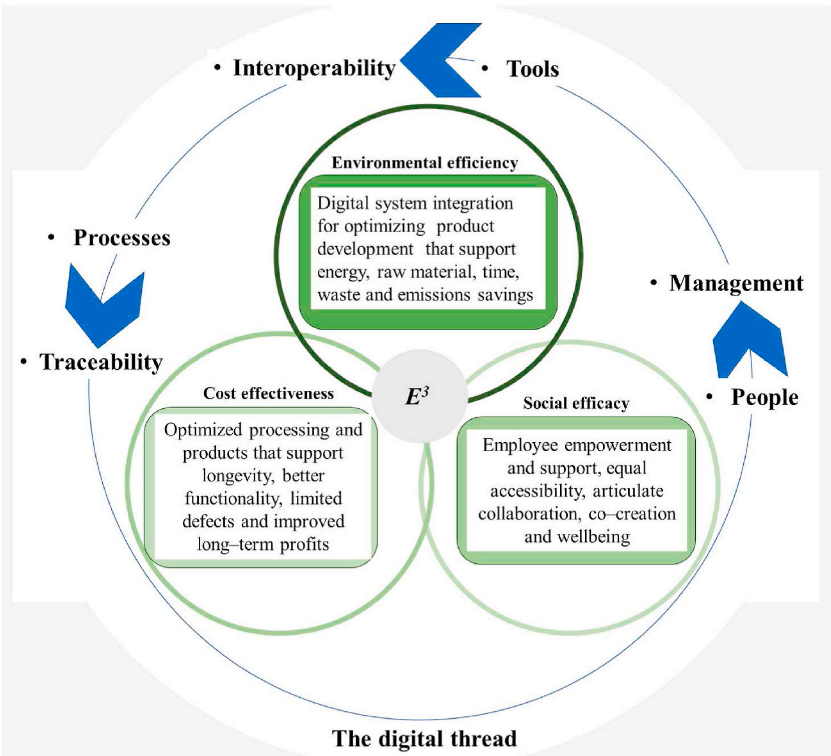


Fig. 6. Representation of how AM through the digital thread help achieve E^3 (environmental, economic, and social equity).

Table 3
Examples of workflow and design simulation software in AM (Dassault Systèmes).

Process	Goal	Software	Reference
Design	Define and prepare digital geometric model.	The 3DEXPERIENCE platform (Catia, SolidWorks), nTopology	[136–138]
Shape optimizing/ performance validation	Analyze functional requirement to optimize the part design (topology, lattice structure optimization). Evaluate, verify design performance according to use intent.	Function-Driven Generative Design, COMSOL Multiphysics, Ansys, 3DXpert, Inspire Print3D	[139–143]
Pre-print planning and simulations	Automate part positioning on the platform and allow interaction. Automate 2D slicing and relevant supports. Select process parameters. Plan part packing Run virtual manufacturing to analyze performance.	3Dexperience SIMULIA, Materialise Magics, Netfabb, 3DXpert	[141, 143–146]
Monitoring and quality	Perform quality check of process. Evaluate consistent control.	Ansys, EOSTATE, ExposureOT, Sigma Lab's IPQA™	[142,147, 148]

In terms of differences, lattice optimization uses a repeating pattern of beams or struts, while honeycomb optimization uses interconnected cells. Both lattice and honeycomb optimization methods are subtypes of topology optimization, which involves optimizing the layout of a structure to achieve light weighting and enhanced mechanical performance [153]. The choice between topology, lattice and honeycomb structures for optimizing product designs depends on the specific requirements of intended application. These may include application constraints, manufacturing constraints, performance function, and cost function [153,154, 160–162]. Lattice structures are ideal for applications requiring high strength-to-weight ratios and energy absorption [163], while honeycomb structures are best suited for maximizing strength and stiffness. Studies [24,164] offer exemplary scenarios when a particular structural optimizations method may be preferrable to the other.

3.3. Enabling sustainable metal AM through design optimization

The AM categories used for metal parts include BJT, DED, PBF, MJT and MEX [66,69,106,165–167]. The as-build parts (commonly referred as green part) from BJT, MJT and MEX are inherently fragile with limited detail and mechanical properties [106,168]. The start-up material is often a mixture of metal powder and binder, usually a polymer. Mandatory postprocessing is required to decouple the actual part and binder. Post-heat treatment (sintering or infiltration) of the green part with/without infill material is also required to achieve final density and required properties [128,166–168]. DED and PBF are the most suitable methods to build fully dense end-use metal parts (e.g., steel alloys, titanium alloys) due to their maturity level [128,168–170]. The maturity of AM system is classified with offered high stability and availability [171].

Stainless steel (SS) alloys are one of the earliest and most utilized metallic powder materials in AM. These materials are widely used for several structural parts in transport and other industrial applications due to their characteristics. The steel industry is one of the most energy and CO_2 intensive industries globally consuming 5.9 % energy [172] and about 6–9% CO_2 emissions [173]. There is the need for different industrial sectors to find new ways to contribute to already ongoing efforts of the steel sector in combatting energy intensities and emissions. One way is to optimize product design to reduce raw material consumption and other manufacturing phase inefficiencies. Lightweighting of SS parts that can be leveraged via AM and simulations enhances cost-effective, resource-efficient superior parts and minimize indirect energy consumption with better material utilization. Optimized and lightweight parts offer better functionality and easy handling. Superior parts allow substantial use-phase energy and operational costs efficiencies. Some common sustainability indicators in AM include cost and energy [126].

Stieberova et al. [40] in a study performed a comprehensive life cycle assessment (LCA) and life cycle costing (LCC) covering all life cycle stages for L-PBF and CM manufactured metal mold intended for die casting. The paper quantified the environmental and economic benefits of producing metal mold intended for zinc parts for automotive application. The study showed higher environmental impacts and raw materials costs for the powder feedstock used in the L-PBF. Nevertheless, the manufacturing phase and use phase of L-PBF route and mold had minimal environmental impacts compared to the die cast route and mold in most of the evaluated categories. Exemplary identified benefits of L-PBF route and mold usage include novel mold design, shorter production time, lower cumulative energy demand, life cycle cost and GHG emissions making AM a better sustainable option than CM.

Despite the numerous benefits metal AM offers to enhance performance and productivity, there exist some challenges that continue to limit its acceptance. Metal L-PBF for instance is criticized for the high energy intensities during manufacturing [40,126–128]. L-PBF intrinsically produces process-specific part defects such as distortion, shrinkage, porosity, delamination of layers, and thermal stresses [120,174]. Luckily, these can be controlled with the right product design, process parameters selection and quality control [78]. The manufacturing plan sometimes requires vast effort and time in identifying the suitable processing parameters and conditions that go beyond a printable feature. Support structures (hereafter referred to as supports) are created geometries that provide a base and anchor for the actual part to the build plate during the building process. Supports are required to provide support for overhang features and to dissipate heat away to prevent thermal defects [67,175,176]. More complex or more organic shapes require support all around which sometimes increases post-processing efforts. Supports are sacrificial features built along the useful part to ensure successful build. Supports sometimes add to manufacturing time and raw material usage. Hence good planning is required to ensure their effective designs and volume in consideration to offer the needed function of anchor and heat dissipation. Designing an easy-to-remove support helps to reduce the volume of the supports (less wasted material) and minimize post-processing costs (time and effort) [176].

Metal AM is controlled by several process parameters [129,177,178]. The selection of process parameters and the aspects they control have been discussed in literature [133,179–182]. The several affecting process parameters in L-PBF for the different process phenomena and environment condition often require separate set-up optimizations. Identifying the optimal settings (e.g., process parameters and condition) in metal AM can be time consuming, challenging and may require a set of different individual experiments [129]. This sometimes increases costs and creates difficulty using L-PBF [121,129] as there are no fit-for-all rules. These complicate the controlling of a build cycle, an example of barrier to developing a real-time closed-loop controlling in AM [121]. Simulations are promising in identifying the most optimal printable features [140,183] and processing setup (e.g., process gas) [184].

3.4. Simulation-assisted product design via DfAM for AM

A product design in AM includes the optimizing of all factors including geometric shape, material choice, process parameters, post-processing and so on as opposed to traditional product design steps. The digital thread and digital twin capability of AM allows a digital integration of systems, software to simulate part design iterations and manufacturing route thereby reducing the need of physical steps and commitments. Digital twin can be described as the real-time virtual counterpart that is capable to mimic/mirror its physical product or process [23,185]. Digital twin capabilities allow users visualize, capture, predict and optimize key indicators of a system to make informed decisions prior to physical undertaking [186,187]. A digital thread can be defined as a seamless communication and integration of manufacturing assets and elements throughout the different LC phases of a manufacturing system [21]. Digital thread connects manufacturing systems data and processes for smarter production, products and integrated ecosystems [188]. Digitalization allows to achieve right-first-time parts, efficient manufacturing time and efforts related costs from the onset of product design. DfAM guidelines help AM users with a step-by-step approach to selecting the best designs and controlling processing parameters [183,189]. Digitally optimized components reduce energy utilization, material consumption and create new business models through the digital thread. The use of digital tools in AM enables simulation at every step of the product design prior to physical printing. Design optimization via generative design and pre-printing simulation play a vital role in terms of product design and manufacturing optimization. Computer-based software allows users to virtually design and visualize the performances of products under different loading conditions [64,145,190]. Simulations are also used to integrate control systems at the initial stages of the design process. This allows users optimize and select the best designs, machine parameters, material configurations build layout along the design process. This approach potentially reduces or eliminates the physical process of trial-and-error testing.

4. Case study

The outcome of the literature review was used as basis of the case in this study, with focus on product design and manufacturing planning optimization using generative design methodology and PBF build software for achieving design optimization (topology, honeycomb, lattice), cost efficacy (reduced time and mass) and efficiency (combined build for time and volume). This study uses computer-based design modelling and simulations utilizing L-PBF processing parameter values, and SS 316L properties to investigate dependencies between part weight and time on function and resource efficiency. This pair was selected because it is the most commonly applicable combination with well-defined system manufacturer processing parameter. The virtual DfAM cases were performed to ascertain potential benefits of digital representations, designing and simulation. The study shows the respective influence of part design optimization and build layout on part weight and build time. The ideation particularly considered topology, lattice and honeycomb structures optimized designs. The study considers (1) the different product optimization methods and (2) the build plan suitable to offer the needed weight reduction and minimize required supports, the build time and removal efforts as well.

The aim was to investigate to what extent simulation-driven design optimization influences resource consumption from aspects of (1) part weight which also determine the amount of used raw material and (2) manufacturing time which also affects the rate of energy consumption. The goals of the design were to reduce part weight, optimize material usage, reduce production time and costs. The design optimization aimed to achieve the best stiffness-to-weight ratio with 50 % material reduction. The assumption of the study is to reduce the manufacturing time and build volume using combined for the comparable structural optimization methods, topology, honeycomb, and lattice.

4.1. Methods and materials

This study used computer-based software to define, design, and plan manufacturing processes for a SS cantilever plate based on Electro Optical Systems (EOS) M290 machine according to past studies of Clark [130], Arora [131], Leirmo and Martinsen [134], Thompson et al. [135]. Dassault Systèmes SolidWorks, nTopology nTop, Materialise Magics, and EOS EOSPRINT were used for the virtual design case.

CAD model of the original solid cantilever plate was designed using SolidWorks. Plate dimensions were 100 x 50 $\times$ 5 mm (length, height, and width respectively) and weighed 197.5 g. Initial cantilever plate CAD modelling and stress-strain simulations for topology optimization were carried out with Dassault Systèmes SolidWorks to approve a simplistic case study example with the initial geometry and handling under a theoretical load case. A simple finite element analysis (FEA) was virtually performed for static stress and displacement tests to compare structural performance. Structural constraints (fixed) were set to the left side of the wall, and a structural load of 100 N was applied along the edge of the plate in the case of PARTs A and B.

Final design variations were continued with nTop to generate a more precise topologically optimized model together with honeycomb and lattice structures variations. The design mass reduction was initially set to be 70 % for PART B and later thickened to 50 % as using 50 % mass reduction constraint created one lump of mass since nTop does not have an option to limit the maximum thickness of the material. A 1 mm thickness was added to the entire body after which material that went over the design space were removed. The four plates hereafter referred to as PART A: solid design; PART B: topology design; PART C: honeycomb structure design and PART D: lattice structure design.

Pre-planning of build set-up was performed with Magics and EOSPRINT to optimize build layouts (orientations, supports and build capacities). A general overview of supports and part volume during the build plan were considered in relation to optimizing build time. Supports structures were generated with Materialise Magics with a 45° overhang restriction in block form for EOS M290 L-PBF machine. A 3 mm height supports section was added to the bottom of each part to anchor them to the build plate and to provide easier removal from build platform after manufacturing. This was done to determine realistic AM conditions for each part variation and printing orientation, and to estimate needed supports volume. Finally, EOSPRINT was used to plan part placement on build platform and to determine build times for each part variation with batch sizes of one and ten parts. Building parameters were set as "316L 40 μm FlexLine1.X" provided by the system manufacturer in EOSPRINT for the EOS M290 machine. The estimated build times were compared for the different optimization methods to ascertain how respective given times respond to each other. Table 4 shows the defined parameters and material data for the design case.

Fig. 7a and b represents the comparable part orientations used in virtual build study.

5. Results and discussions

The virtually generated time for manufacturing the cantilever plates derived with the two build scenarios (1) single part and (2) ten parts individually for the PART A, PART B, PART C, and PART D are summarized in Table 5. The tabulation highlights the main differences between the base cantilever plate and the optimized designs.

Table 5 shows simulation results of outlooks of the comparable parts. About 78.4 g of mass was saved with the initial SolidWorks topology optimization which translates to about 40 % weight reduction. The fine-tuned topology optimized with nTop further reduced the topology optimized plate by about 10 g. The honeycomb optimization resulted in 89.9 g cantilever plate saving about 55 % weight. The lattice optimization resulted in about 61 % weight reduction making the optimized part about 120 g lighter.

The comparable displacement and stresses for PART A and PART B show an increased structural behavior in the latter. The structural performance of PART C and PART D are comparable to the base cantilever plate as the effect of the loading could not be virtually evaluated. The case parts might pose a few assumed limitations in terms of printability under real manufacturing conditions. Fusing large surface areas during a single pass would most probably cause warping of the structure which would happen for example in the first layers of Parts A, C and D in a physical print. Strongest warpage effect would be seen in the horizontal samples and lower section of vertically printed part B, which would lead to dimensional inaccuracy. The build layouts found to be most effective with build height of 50 mm compared to the vertical alternative are shown in Table 6.

The resulting build weights and times for the different build orientations using the EOSPRINT are shown in Table 7.

Table 7 shows the effect of design optimization and build orientation on manufacturing time. The orientation and form of optimizations influence the build volume thus may either increase or decrease the total build times in agreement with study [176]. Comparatively the manufacturing times in this study showed differences in time for the separate single and combined builds for the horizontal and vertical orientations. A comparison of the shared build times for the horizontal orientation with supports showed approximately 2.5 h, 2.8 h, 2 h and 1.41 h respectively for the combined build for PARTs A, B, C and D. Comparatively, the shared time per a part in the combined builds compared to the single build demonstrates how L-PBF enhances resource efficiency via simultaneous multiple part manufacturing. The main contributor to time saving is the shared recoater and platform moving times, as this remains constant per build cycle irrespective of the number of parts. The combined build also uses nearly the same quantity of start-up powder to build multiple parts. This is because the different machine systems require a specific amount of startup powder to ensure a successful build cycle. Maximizing a build cycle with multiple parts reduces the amount of start-up feedstock and other process aids that would otherwise be required for single build cycles.

Through combined build, manufacturing times can be reduced by means of maximized volume utilization. Combined build gives a share value of energy used in warming the build chamber, idling, platform moving, recoater moving, and other process auxiliaries (e.g., shielding gas). The advantage of these features is reduced costs in design and manufacturing phases. Fig. 8a and b demonstrates

Table 4
Tabulation of build parameters (single laser) and material property.

Process parameters	Value			
Layer height (mm)	0.04			
Recoat time (s)	9			
Maximum part and support height (mm)	50 + 3 (based on horizontal selected orientation and support)			
Part volume (m/ρ) (mm^3) without supports	PART A	PART B	PART C	PART D
	25000	12725	11457	9270
Part volume (m/ρ) (mm^3) with supports	25609	15223	15813	10794
Average build rates (mm^3/s)	3.01	1.69	2.63	2.57
Material property	Density (kg/m^3)	Modulus of elasticity (GPa)	Poisson's ratio	
Value	7900	210	0.3	

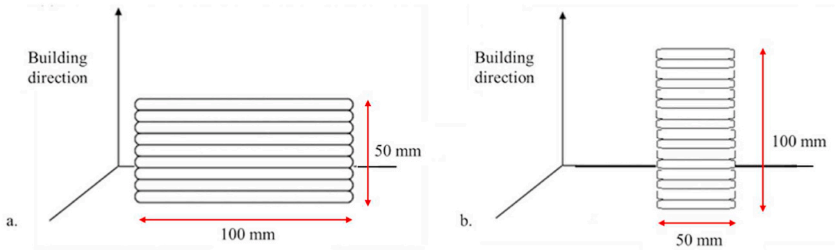
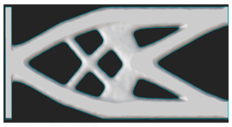
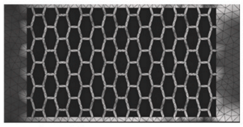
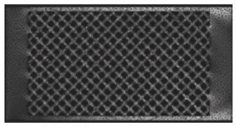
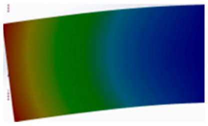
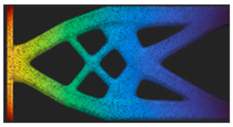
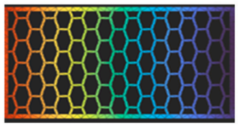
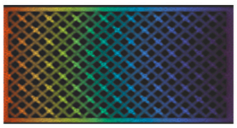


Fig. 7. Representation of build orientations, a. horizontal, b. vertical.

Table 5
Examples of workflow and design simulation software in AM.

Form of plate	PART A	PART B	PART C	PART D
Type of structure	Solid	Topology	Honeycomb	Lattice
				
Weight (g)	198	110 (-44%)	89.9 (-55%)	77.9 (-61%)
Structural validation				
				
Stresses (MPa)		8.77	15.6	26.8
Displacement (mm e-3)	3.81	9.74	15.7	25.7

relations of design optimization methods, part orientation, platform utilization and build volume on time.

As can be seen from Fig. 8, the build orientation influences build time (see blue, orange, grey and yellow bars, and lines) in Fig. 8a and b. The horizontal lattice structure (PART D) offered the most optimal time followed by the honeycomb (PART C). Main difference between horizontal and vertical build times comes from increased build height in latter, which leads to longer recoating times. This is the case with parts A, C and D where exposure time with laser and support volumes remain similar with both horizontal and vertical orientations, while recoating time is increased in vertical orientation. For part B, the vertical orientation imposes notable decrease in required supports, which leads to decrease in required exposure time. This effect can be seen as longer build time with larger amount of horizontally manufactured B parts (e.g., 10 parts), where recoating time remains shorter for the horizontal orientation, but exposure time increases notably. Therefore, vertical build orientation would be more optimal for part B if a high number of parts are manufactured in one go. For parts A, C and D, horizontal build orientation remains more time-efficient regardless of the number of parts produced in a build cycle. The determinate here for choosing the most optimal design cannot therefore solely be based on the final part design weight. Other factors such as orientation and build volume utilization capable of affecting build time, raw material, etc. must be considered from the intent of the design goals.

The case presented in this study illustrates how DfAM via digital thread can be used to make informed design and manufacturing choices from the start of a product design in agreement with [143,148,190–192]. Agreeable to studies [16,17,140,183], simulations were used to design lightweight and intricate designs and to virtually optimize the build process. This study through the case study has shown that other aspects of the product design process equally need to be optimized to maximize the benefits offered by AM. For instance, using easy to remove (by hand or with a soft hit with hand tools (e.g., rubber mallet/hammer)) supports between the actual parts and build plate can quicken post processing and omit the need of demanding sawing/machining.

This study shows that although AM offers the flexibility to make more sustainable and functional components, the method cannot entirely replace CM. Parts manufactured with AM, especially metal parts, often require a CM for removing the parts from the build plate, separating the supports and to post-process the as build parts to bring them to the required dimensional stability and reliability.

The evaluation of the build time for the different build orientations and the number of parts in a build cycle shows the added value of combined build benefits that can be achieved when using L-PBF. Manufacturing cost and energy are directly affected by the build time in a manufacturing process. The time taken to produce components directly affects the total energy consumption, thus reducing build time via optimized parts is vital to reducing energy consumption during the manufacturing phase of a product. The reduced

Table 6
Representation of horizontal build orientation, orange-colored regions indicate supports.

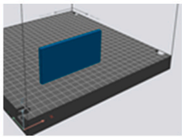
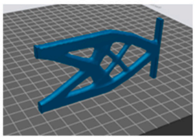
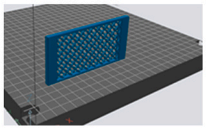
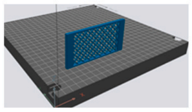
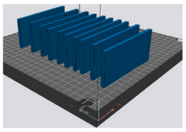
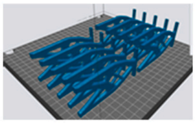
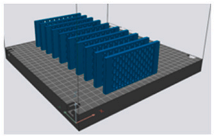
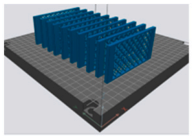
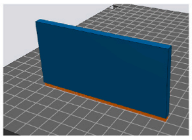
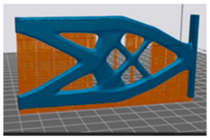
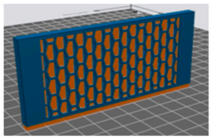
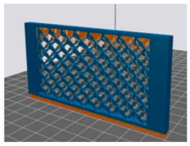
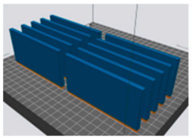
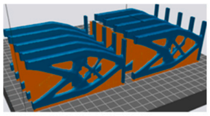
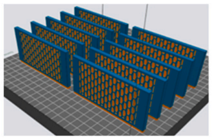
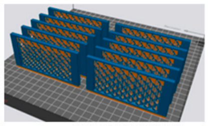
Form of plate	PART A	PART B	PART C	PART D
Single build 1 part per build cycle without supports				
Multiple build (10 part per build cycle without supports)				
Single build (1 part per build cycle with supports)				
Multiple builds (10 parts per build cycle with supports)				

Table 7
Resultant build weight and time based on the two build orientations for parts with supports.

Form of plate	Build weight (kg)		Print time (h)			
	Horizontal orientation	Vertical orientation	Horizontal orientation		Vertical orientation	
	Per one (1) part	Per one (1) part	Per one (1) part	Per ten (10) parts	Per one (1) part	Per ten (10) parts
PART A	202.3	199.9	5.33	25.4	8.42	29.1
PART B	120.3	106.3	5.49	28.3	7.41	18.6
PART C	124.9	133.1	4.59	20.0	8.03	22.4
PART D	85.3	82.5	4.28	14.6	7.35	17.6

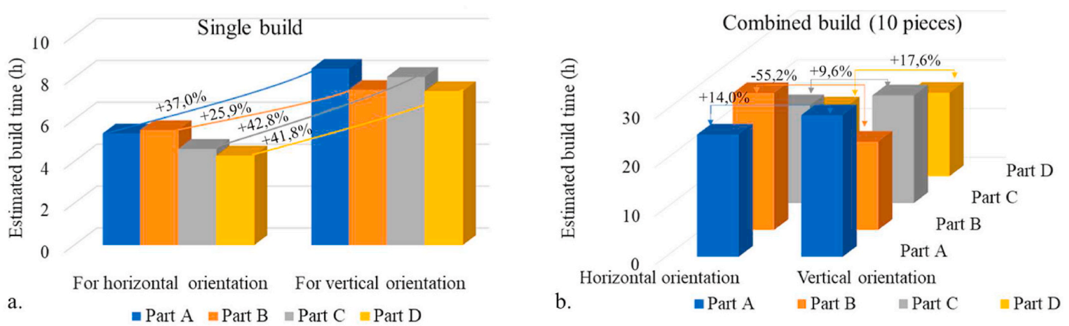


Fig. 8. Representation of the impact of design optimization method, a. part orientation, b. platform utilization on build time.

manufacturing time highlights how optimized designs, optimal build orientation and combined manufacturing affect L-PBF efficiency. The lightweighting achieved for PART B, PART C and PART D can potentially improve performance of dynamic applications e.g., transport sector, for instance can reduce fuel consumption and emissions levels based on the study [57,60].

Resource efficiency offers sustainable and cost-effective routes to achieving SM. Simulation assisted modelling can design optimized components with increased functionality, added value and cost reductions. The identified benefits of the design system (designing and manufacturing) to improved functionality and efficiency are shown in this study. Virtual simulations help to quicken product development (e.g., designing, building, and testing) during product development and help find the best features for the needed results. The possibility of iterating design cycles virtually reduces efforts and time related costs and aids to omit part failure and non-productive production runs. Many a times, a designer may focus strongly on the design optimization aspect and neglect the need to optimize other aspects (e.g., process parameters, orientation, build volume etc.) which equally affect energy consumption, raw material consumption, time, and effort related costs.

The main outcome from this study is the identified elements that can be optimized in L-PBF to enhance resource efficiency towards sustainability. This study highlights ways in which AM aid SM practice via computer modelling and simulation. Simulation and CAD modeling tools are powerful tools that assist in designing, creating, and evaluating manufacturing systems as shown in the case study. The use of optimized, lightweight component designs and combined multiple part build enhance raw material and indirect energy efficiencies. L-PBF can flexibly be used to build efficient product designs that can customize and vary the quality and properties of the final parts. Simulation tools in AM are shown to aid fast and flexible design iteration without machine (e.g., tools and fixtures) imposed constraints.

The digital thread of AM supports and harnesses effort toward sustainable business operations. These integrations help monitor build to predict defect, control physical inventory with virtual inventory and data management, thereby enhance productivity and minimize potential errors and commitment cost. The capability of on-demand manufacturing via digital thread eliminates the need for physical parts stocking thereby reducing resource consumption which otherwise would be used.

6. Conclusions

The influence of AM (i.e., L-PBF) on resource efficiencies, particularly weights and manufacturing time were evaluated in this study using literature review and a virtual product design optimization case study. The primary outcome of this study is the identified means including optimized designs and build plan by which AM can be used to enhance process efficiencies. The study shows that L-PBF, a subcategory of PBF enables the creation of energy efficient products capable of reducing or eliminating waste and pollutants. As shown in Table 5, Table 6, Table 7 and Fig. 8, L-PBF allows sustainable product designs in respect to light weighting, reduced volume and time to enhancing structural improvements, and resource effectiveness. Achieving such goals via L-PBF leverages sustainability aspects especially with resource efficiency through combined builds and reduced part weights similarly as shown in the study of Qin et al. [126]. The design case performed in this study confirms the benefits of simulation-assisted tools to product designing, testing, and process planning. Simulation-generated product designs can control energy consumption, raw material consumption, manufacturing time and performance.

Several collaborations are formed at various industry levels within science, engineering, commerce and others towards achieving SDGs. Undoubtedly, implementing and supporting such collaboration in AM along other modern technologies are promising to promoting sustainability. AM through other I4.0 technologies empower industrial designers and manufacturers to unprecedented product designs and swift productions capable of improving quality, reliability, and efficiency. AM can help achieve aspects of the SDGs through superior parts, decentralized manufacturing, better resource efficiency, minimized emissions, and many more. Proponents and opponents must extend AM sustainability discussions to include all the lifecycle phases and application levels to gain a good understanding of its contributions towards sustainability.

6.1. *Limitations and further research directions*

This study has proven that digital tools used along the application of DfAM rules simplify and optimize the product designing process in AM. The case study includes only virtual evaluation of design and build optimization in AM to access their potential impact on mechanical performance, build time and raw material consumption. The influences of build orientation, supports and build volume on manufacturing time considered in this study require physical build experiment to ascertain the virtual results. Regarding dimensional accuracy, all parts would inhabit some level of inaccuracy due to the nature of L-PBF. For instance, stair-step effect on tilted surfaces (high surface roughness) and anisotropic shrinkage of parts due to layer-by-layer build method. Notably, selecting a suitable support capable of achieving successful printing and adequate dimensional accuracy particularly with metal materials can omit or diminish this limitation in AM.

We recommended scholars to investigate the impacts of different supports, build angles, and post-build removal efforts on resource efficiency through virtual and physical studies. Potential to realistic evaluation of performance (e.g., printability, dimensional accuracy) and build time related costs. Further studies could also include physical testing of design loading conditions and to evaluate how well a metal AM parts satisfy structural performance and design goals.

Data availability

Has data associated with your study been deposited into a publicly available repository?
No.
Data will be made available on request.

CRediT authorship contribution statement

Patricia Nyamekye: Writing – review & editing, Writing – original draft, Visualization, Supervision, Investigation, Data curation, Conceptualization. **Rohit Lakshmanan:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Vesa Tepponen:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis. **Sami Westman:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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