Cleaner Engineering and Technology 13 (2023) 100620

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

journal homepage: www.sciencedirect.com/journal/cleaner-engineering-and-technology

The convergence of lean management and additive manufacturing: Case of manufacturing industries

Rohit Lakshmanan [a,*], Patricia Nyamekye [b], Veli-Matti Virolainen [a], Heidi Piili [c]

[a] *LUT Business School, LUT University, FI-53850, Lappeenranta, Finland*
[b] *Research Group of Laser Material Processing, Department of Mechanical Engineering, LUT University, FI-53850, Lappeenranta, Finland*
[c] *Department of Mechanical and Materials Engineering, University of Turku, FI-20500, Turku, Finland*

ARTICLE INFO

Keywords:
Additive manufacturing
Lean management
Sustainable manufacturing
Productivity
Resource efficiency

ABSTRACT

Lean practices in industry offered by lean management (LM) tools have revolutionized industrial production and operation. These tools allow for incorporation of pragmatic steps to reduce waste, improve flow of goods, and increase productivity in industrial settings. Novel manufacturing methods such as additive manufacturing (AM) promotes resource efficiency and cost efficiency which already is offered by LM. AM also aids in further waste minimization through light weighting, reduced scrap rate, shorter lead time, digital inventory, and energy-efficient parts. A preliminary review showed a lack of data on how LM and AM complement each other towards elimination of waste created. The aim of the study was to assess the prospect of the convergence of LM and AM to enhance resource efficiency and reduce waste, as well as the contribution to environmental, social, and economic aspects, i.e., the pillars of sustainability. The study methodology reviews literature of LM and AM including key concepts, tools, and technologies, and two industrial case studies of new product developments. The results show a distinctive stepwise approach by which organizations may identify and reduce waste in their operations by reduced cost, time, space, material usage, emissions, and digitalization. The novelty of the study is in addition to environmental benefits such as reduced emissions and reduced material waste, the convergence of LM and AM also contributes to economic and social sustainability, for example, through on-demand manufacturing which can provide better supply chain efficiencies, customized batch production, reduced lead time, etc., as well as reduced human fatigue and errors, workspace safety, ergonomic working, etc., respectively. The integration of LM and AM also reduces overproduction, process steps, and total cost of ownership through reduced need of physical spare parts. In this way, outdated or unmatched parts can be omitted, and replaced with on-demand manufactured AM spare parts.

1. Introduction

Productivity has been one of the main goals of industries and formed the basis of measuring operational excellence in the past (Jbira et al., 2020). Different industries consume resources distinctively to produce goods and services to satisfy human needs. Tangible, intangible, natural, and non-natural resources such as raw material, energy, infrastructure, knowledge, etc. (Bag et al., 2020), contribute to dynamic capabilities drivers. Dynamic capabilities are defined as “the firm’s ability to integrate, build, and reconfigure internal and external competencies to address rapidly changing environments” (Teece et al., 1997). These capabilities are necessary for the continuous functioning of industrial activities. Increasing concerns of resource depletion, volume of waste created and emissions into the biological ecosystem have and continue to alter organizational activities capable of addressing the concerns. Industrial sectors have continued to rethink used methods and processes from a technical standpoint to minimize and/or omit potential negative impacts. Existing and emerging industrial sectors are developing intuitively resource efficient methods and strategies capable of enhancing productivity (Schiuma, 2009), customer involvement (Bogers et al., 2016) and sustainability (Daraban et al., 2019; Wits et al., 2016).

Abbreviation	Expansion
AM	Additive manufacturing

(*continued on next page*)

---

* Corresponding author.
E-mail addresses: rohit.lakshmanan@lut.fi (R. Lakshmanan), patricia.nyamekye@lut.fi (P. Nyamekye), veli.matti.virolainen@lut.fi (V.-M. Virolainen), heidi.piili@utu.fi (H. Piili).

https://doi.org/10.1016/j.clet.2023.100620
Received 24 November 2022; Received in revised form 6 March 2023; Accepted 14 March 2023

(*continued*)

Abbreviation	Expansion
CAD	Computer-aided design
CAE	Computer-aided engineering
CFA	Confirmatory factor analysis
CO_2	Carbon dioxide
DfAM	Design for additive manufacturing
GHG	Greenhouse gas
JIT	Just-in-time
LM	Lean management
NVA	Non-value added
PBF	Powder bed fusion
SDG	Sustainable development goals
SM	Sustainable manufacturing
STL	Standard tessellation language
TPE	Thermoplastic elastomer
TPS	Toyota Production Systems
UN	The United Nations
3D	3-dimension

The Brundtland Report (1987) defines sustainable development as development that “meets the needs of the current generation without compromising the ability of future generations to meet their needs”. Sustainability may be considered from the environmental, economic, and social aspects: which are the *three pillars* of sustainability (Ghobadian et al., 2020). The United Nations (UN) (2015) introduced 17 Sustainable Development Goals (SDGs) as a benchmark for nations and organizations to take steps to promote peace and prosperity for the planet “now and in the future”. These goals include, for example, affordable and clean energy, responsible consumption and production, partnership for the goals, etc. Hence, smart production systems, low carbon technologies, resource efficiency, circular economy, etc., should be integrated into the strategy of organizations to meet sustainability goals and operational excellence (Tonelli et al., 2013). By learning, rethinking, and implementing new industrial practices and business models, organizations can develop new methods which are capable of reducing resource consumption, waste creation and shortening production times (Godina et al., 2020; International Organization for Standardization, 2021). Additionally, the skills of the workforce must be updated to match with these new strategies, with the help of management in these organizations through training, knowledge transfer, etc., to obtain and maintain their commitment to their goals (Galpin et al., 2015).

Lean management (LM) and sustainable manufacturing (SM) are examples tools that foster resource efficiency, superior part performance, process optimization, energy-efficient manufacturing and products, and improved productivity (Abualfaraa et al., 2017; Aljinović et al., 2021). LM in particular focuses on the reduction of waste and increase in productivity, while also having a strong affinity towards value, customer satisfaction and employees’ skills. Some impacts that LM have on an organization are related to leadership and governance, employee engagement, learning/teaching, integration of standardized work practices, and effective results which are showcased repetitively (Jbira et al., 2020). SM is defined as the development of products via economically-sound processes with minimized negative environmental impacts while conserving energy and natural resources (US EPA, 2020). The sustainability centricity of the current industrial era promotes productivity, customer satisfaction, profitability, and is capable of averting future costs. However, customer demand for high valued customizable products may make it difficult to adhere to the goals of LM, i.e., reduced resource consumption (Chronéer and Wallström, 2016). Smart and sustainable manufacturing technologies coupled with LM may be able to provide high value optimized products while also considering aspects of sustainability.

Additive manufacturing (AM) is an example of an emerging manufacturing method that offers unprecedented and multifaceted designs to achieve lean and sustainable goals (Boer et al., 2020; Daraban et al., 2019). AM offers several possibilities to manufacture superior, individualized, efficient parts, effective manpower skill while reduced lead times and process steps (Wiberg et al., 2019). These benefits are promising to increase economic benefits (e.g., return on investment (ROI) and life cycle costs), social demands (e.g., consumer-centric parts, workers retention) and reducing negative environmental impacts (Costabile et al., 2016; Gebisa and Lemu, 2017). An integration of LM and AM can help organizations to achieve operational and production goals such as added value, high productivity, sustainability, and customer satisfaction (Bag et al., 2020; Jbira et al., 2020). Additionally, LM and AM integration can offer competitive advantage to match the dynamics and complexities of changing market setting through product differentiation and service offerings. (Garza-Reyes et al., 2014; Kumar et al., 2021).

The extant literature however is scant regarding the integration of LM and AM. This paper contributes to close the research gap and build on extant literature regarding the integration of LM and AM (Kumar et al., 2021) through stepwise evaluation and application of the points of convergence of LM and AM and how these contribute to environmental, economic, and social aspects. Companies that seek to adopt an integrated AM and LM strategies must be able to understand the synergies of both to support effective decision making. This integration applied with critical consideration of the potential of convergence can aid organizations achieve their productivity, customer satisfaction, operational efficiency, and sustainability goals. Nevertheless, there is a lack of relevant studies to support the mainstream uptake of AM as part of the manufacturing chain. It is for this reason that this review was carried out in relation to formulating research questions (RQ) and answers. This way, manufacturing sectors may understand the relevance, novelty, and state-of-the-art to identify practices by which AM applicability may support decision making to improve leanness. The study aims to answer three main research questions.

RQ 1: Does AM correlate to LM and to what extent are such relations previously studied if any?
RQ 2: How do the current trends in LM and AM research enable a decisive industry adoption of AM?
RQ 3: What influence can the capabilities of AM have on lean practice within manufacturing industries?

RQ1 and RQ2 were answered via an in-depth analysis of existing literature on the tools, technologies, and concepts related to LM and AM. RQ 3 was answered with industrial case studies, highlighting offered potential such as product design optimization, reduced manufacturing steps and time, through via simulation assisted product designs for additive manufacturing.

2. Research methodology

The study uses literature review of web bases and existing industrial cases relevant to this topic. This study conducted a structured review of peer-reviewed articles, conference papers, and company data that engaged critically with the explanation of the identifications and associated elements, categories, benefits as well the limitations of LM and AM. These approaches have been used in several studies to demonstrate new knowledge and complex trends to aid understanding and assimilation. Exemplary topics includes “sustainable manufacturing”, “additive manufacturing, “industry 4.0”, “advance manufacturing security systems” by (Galati and Bigliardi, 2019; Grasso and Colosimo, 2017; Miller et al., 2010; Moldavska and Welo, 2017; Trappey et al., 2016; Wits et al., 2016) and “sustainable supply chain” and “lean thinking” by (Ahi and Searcy, 2013; Christopher and Ryals, 2014; Chronéer and Wallström, 2016; Hines et al., 2004).

A broader scope of search from Google Scholar of publications indexed in Scopus, ScienceDirect Research Gate, and IOP Conferences was carried out. The choice of keywords combinations and appropriate use of Boolean operators were carefully considered to ensure the accuracy of the search results. The combination of the keywords and Boolean operators (AND, OR) used were "lean management" OR "lean manufacturing" AND "additive manufacturing" OR "3d printing". Keywords were extended to include "lean manufacturing" to extract studies that consider lean thinking from the point of manufacturing. The requirement for the search was that either the title, abstract, and/or keywords should contain "Lean management", "Lean manufacturing" and simultaneously mention "additive manufacturing" and/or "3D printing". The selected search keywords broadly cover these study aspects that can affect the analysis needed to draw conclusions. The initial search hit of from Google Scholar containing almost all considered indexed databases was 571 publications which indicated the topic was under-explored. There exists a gap in literature in relation to LM concepts in AM.

The detailed review limited to Scopus and ScienceDirect indexed Conference paper, Article, Conference review, Book chapter, Review publications. The outcome of this narrowed web search with "lean manufacturing" or "lean management" AND "additive manufacturing" or "3D printing" gave twenty (20) and thirty-nine (39) publications from ScienceDirect and Scopus respectively. The combination of "lean manufacturing" and "additive manufacturing" or "3d printing" gave a total of one hundred and thirty-four (134) publications whereas "lean management" and "additive manufacturing" or "3d printing" gave one hundred and seventy-eight (178) documents on ScienceDirect. The data collection was limited to the years 2010–2023 to ensure that the current trends were used for this study. The number of articles that fulfilled the search criteria after eliminating duplicates are as Table 1.

Direct observation was used to identify the most related publications to perform the review and describe conceptual understanding. The result of this cross-sectional study was utilized to analyze the convergence of LM and AM in fulfilling the aim of this study. The collected data were further characterized into year and research fields mainly with Science Direct publications as it offered such classifications for further analysis. Fig. 1 illustrates the increasing trend of publication based on the analysis from the year 2012–2023.

Fig. 1 shows that the number of publications with the keywords have grown from one (1) publication in 2012 to thirty (30) in 2023. The steady rise in the number of publications shows that academic interest is growing. One reason for growth could be demand from industry to solve problems in operations through emerging technologies with an integrated high-level management system. The growth in the number of publications indicates a growing importance and need for research in this field t of sustainable practices.

The growth of AM along with lean concepts is still relatively unexplored in comparison to them separately. Fig. 2 shows the main subject areas of research for the same keywords.

Fig. 2 shows that engineering and technical sciences related topics have the majority share of research, followed by decision sciences. Topics related to business, finance, management, economics, and accounting have a share only of about 9.2% of the research area. This can be interpreted to mean that majority of LM and AM studies have emerged from the sciences though LM is mostly discussed within business.

Table 1
Selected keywords and Boolean operators.

Keywords	Boolean operator combination	Web base results
"Lean management"	"Lean management" **AND** "additive manufacturing" **or** "3d printing"	ScienceDirect (178) Scopus ()
"Lean manufacturing"	"Lean manufacturing" **AND** "additive manufacturing" **or** "3d printing"	Science Direct (135) Scopus (36)
"Additive manufacturing"	"Additive manufacturing" AND "lean manufacturing" or "lean management"	Science Direct (41) Scopus (31)
"3d printing"	"3D printing" AND "lean manufacturing" or "lean management"	Science Direct (28) Scopus (13)

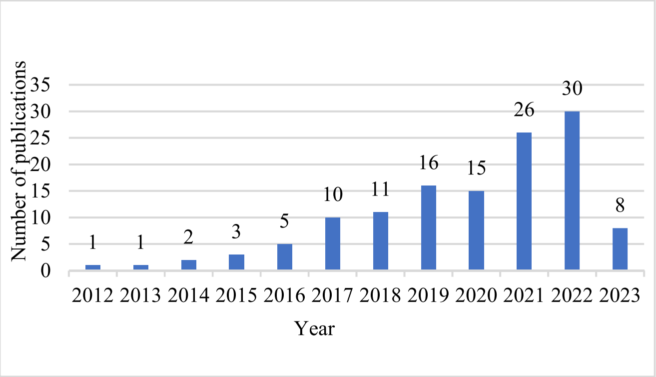

Fig. 1. Number of publications from 2012 to 2022.

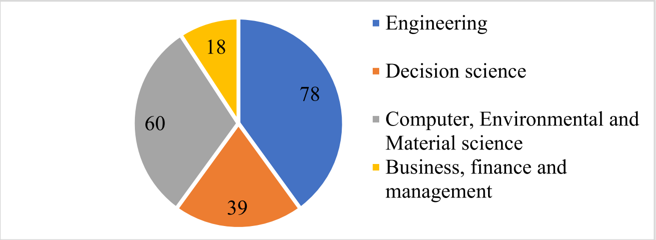

Fig. 2. Areas of research publications on ScienceDirect for the keywords "lean manufacturing" and "additive manufacturing" or "3d printing.

Eighty seven (87) closely linked to this study out of the resultant publications including two (2) industry cases were used in this study. A search of website links was performed to select an applicable case depicting the convergence of LM and AM.

3. Lean management – A tool for achieving waste reduction and operational efficiency

Over the last three decades, LM has been implemented in all industrial sectors. Lean thinking enables industries to optimize production, foster customer engagement, and maximize service resources to reduce waste and drive business growth (Lermen et al., 2023). The aim of LM is the elimination of unnecessary process waste to reduce costs, improve efficiency, increase flexibility and maximize generation of value to customers (Ghobadian et al., 2020). The concept of "lean" was developed by Toyota Motor Corporation in the 1940s in Japan to revolutionize production processes which is known as lean manufacturing (Bittencourt et al., 2019). The term was extensively explored in earlier studies including "Toyota production system and kanban system materialization of just-in-time and respect-for-human system" (Sugimori et al., 1977), "Triumph of the lean production system" (Krafick, 1988), "The machine that changed the world" (James P. Womack et al., 1990) and "Decoding the DNA of the Toyota Production System" (Spear and Bowen, 1999). These studies explicitly highlight the core enablers of Toyota and lean production systems for successful implementation. For instance, Krafick (1988) showed that the performance of automobile industries is tied to parentage and culture and not necessarily by the owner of technological advancement. According to the study, companies that adopt lean need an integrative approach consisting of human resources, machinery, strategies, and emerging technologies for maximized operating performance. Implementation of preventive maintenance ensures that all verticals of the cooperation swiftly respond to change. Spear and Bowen (1999) highlighted reasons why imitators of

Toyota production failed to achieve at targeted goals. The study showed how Toyota creates success using coherence of set operational goals, methods, data, and employee stimuli for the expected results. The strict yet flexible working environment of Toyota production enables for a swift response to unforeseeable circumstances that may affect meeting customer demands and used acquired knowledge to solving problems. Sugimori et al. (1977) highlighted how companies increase performance with the swift response to demand using an exaction order number, right product while maintaining minimized inventory.

The review considered topics such as sustainability, competitive advantage, and organizational management relative to lean thinking for a comprehensive understanding. By creating value through distinct and innovative strategies, organizations can gain a competitive advantage over other market players that do not adopt environment-centric strategies (Agarwal and Helfat, 2009; Barney, 1991). Strategy describes a set of organizational decisions and actions that management make and take to drive growth and to obtain a superior performance relative to competitors (Teece et al., 1997; Teeratansirikool et al., 2013). Strategic planning aids to identify industry niche and as well customers knowledge. Competitive strategy enables a firm to stand against industrial competitive forces to establish a profitable and sustainable position (Porter, 1980). Evaluation of managerial performance factors on cognition, social capital and human capital are also specifically relevant to the strategic focus for the industrial setting (Helfat and Martin, 2015). This can imply that the competitive strategy must be able to produce the intended goals of customer satisfaction as well yield intended organizational performance. Competitive advantages are created when organizations provide novel solutions for their products or services, and the way it is marketed and sold, delivered, and procured (Barr et al., 1992). The concept of lean emphasizes waste reduction, operational resources efficiencies and resource consumption reduction (Chronéer and Wallström, 2016) as an extension to Toyota Production System (TPS) which focuses on cost related waste reduction. In recognition of scarcity of natural resource and high cost of raw material in Japan, TPS was necessitated to avoid waste creation (Sugimori et al., 1977). The two main approaches of lean are: (i) reduction of non-value adding operations or processes and, (ii) reduction of waste creation (Pavnaskar et al., 2003). Value creation is the starting point of lean and considers that value is included in different phases of production (J P Womack and Jones, 1997). Womack and Jones (1997) opined that value must be defined from the specifics of the product and its capabilities from the point of view of the customer. Value adds feature or function to a product, process, or service while removing waste (Hines et al., 2004). Hines et al. (2004) discuss the different types of waste that exist within organizational operations. A holistic and practical understanding of waste is considered from all working processes and is therefore not limited to production waste. Lean thinking seeks to identify activities of the value chain that do or do not add value to the final products. Non-value-added activities are reduced or eliminated and thereby enhance continuous operational improvement at reduced costs (Bittencourt et al., 2019).

There are generally eight (8) types of operational waste that can result from non-value adding activities from the LM perspective. The identified waste includes transportation, inventory, movement, waiting, overproduction, over processing, defects, and skills and is commonly referred to as TIMWOODS (Roosen and Pons, 2013). The first seven types of waste were developed by Taiichi Ohno as part of TPS. The 8th waste type was developed by the western world after their adoption to the TPS.

The 5S system is a widely used tool for implementing LM (Filip and Marascu-Klein, 2015) which denotes “sort”, “set”, “shine”, “standardize” and “sustain”. The method helps standardize daily workplace for obtaining and maintaining continuous orderliness and cleanliness at work. The 5S denotes a five-step method of visual management that aids in eliminating invaluable steps, and to promote cleanliness, ordered markings, labeling of working place and good maintenance (Chiarini, 2013). The acronym “five S” in Japanese and the English translation and as well what they entail are listed in Table 2.

It can be deduced from Table 2 that the 5S system can be used as a general tool for LM to increase operational efficiency. Each of the 5S aims to reduce the amount of waste in either space, time, or practices. The 5S offers an effective means to better organizational performance through an orderly, clean, well-planned workspace capable of promoting workplace safety and increasing product quality. One of the main features of the 5S system is to prepare the work environment to hold visual information. The visual management method assumes that by a simple observation, in a maximum of 5 min, a quick action plan can be used to improve the production process. The production areas, for example, can be marked in colors or markings to show for instance storage areas for production, finished products, reworking, rejected parts, waste storage, dangerous areas, etc. (Filip and Marascu-Klein, 2015).

Shah and Ward (2007) address lean concepts on three levels including: (i) supplier related, (ii) customer related, and (iii) internally or organizationally related. Their study reviewed and identified the relationships of the key lean production of “people” and the “process components”. A confirmatory factor analysis (CFA) was used to narrow down the identified items from the review and company-based data. CFA is a tool that can be used to evaluate the correlation of different factors (Shah and Ward, 2007) to show how related they may be. The study simplifies how different items can be grouped into main components and how to implement them into business frameworks. The results of the study developed ten concepts of lean production shown in Table 3.

It can be seen from Table 3 that the tool developed focuses on organizationally related issues such as pull, flow, setup time reduction, total preventive maintenance, and statistical process control and employee involvement. The focus also is supplier related and customer related. There are several ways to enhance each level of the lean tool. CFA was performed for the 10 factors which provide a value with higher values showing more correlation which range between 0.77 for JIT delivery by suppliers and supplier development (for 2 & 3) to 0.12 for customer involvement and total productive/preventive maintenance (for 4 & 8) (Shah and Ward, 2007). Just in time (JIT) aims to achieve high product quality while using resources optimally through elimination of NVA activities (Aradhye and Kallurkar, 2014). Closely interrelated factors require careful planning, organizing and effort to obtain an efficient and optimal LM system. An adoption to lean practices should be done with an understanding of the individual and combined contributions of the correlations of different factors. “*It is the complementary and synergistic effects of the 10 distinct but highly inter-related elements that give lean production its unique character and its superior ability to achieve multiple performance goals*” (Shah and Ward, 2007).

Table 2
5S system of LM (Filip and Marascu-Klein, 2015).

Practice (English/ Japanese)	Definition
Sort (Seiri)	Separate or remove unwanted resources or materials from workspace by necessary tools
Set in order (Seiton)	Logically organizing and placing the items for easy identification and accessibility. Items must be placed ergonomically to avoid movements or bending
Shine (Seison)	Ensuring clean and tidy work environments, eliminate sources of dirt and minimize waste, perform deep cleaning in a responsible and collaborative manner
Standardize (Seiketsu)	Rules and regulations for storage of products and parts in different areas in a logical and efficient manner. Training the staff on simple visual tools and maintaining standards to reduce search and time wasting
Sustain (Shitsuke)	To ensure continuous improvement, a good feedback mechanism to assess the organizational performance and ensure commitment from all the stakeholders. This is done by monitoring, evaluating, reviewing, and implementing new strategies to achieve desired results

Table 3
General lean items and the levels of interaction (Shah and Ward, 2007).

Factor	Level	Description
Supplier feedback	Supplier related	Transparent and frequent feedback is given to the suppliers about their performance and issues to be solved are addressed.
JIT delivery by suppliers		Delivery from the suppliers should be at the right quantity, place, and time.
Supplier development		Collaborate and resonate with suppliers to involve them more in the production processes.
Customer involvement	Customer related	Understanding customer needs and resonating with their requirements, developing products and solutions around those.
Pull	Internally or organizationally related	Facilitating JIT production while incorporating Kanban.
Flow		Developing strategies to allow easy and continuous flow of products.
Setup time reduction		Reducing the process downtime between product changeovers.
Total productive/ preventive maintenance		Achieving a high level of equipment availability by addressing equipment downtime.
Statistical process control		Ensuring that one process does not cause defects on the product when going to the next flow.
Employee involvement		Involving employees in creative, decision-making tasks.

Other tools for promoting LM include Kanban (Chiarini, 2013) which targets matching the production to the order for the right time to reduce lead time, inventory, and defects with higher quality and reliability. Value stream mapping (VSM) uses graphical representations in an end-to-end manner: from customers demand to delivery of the final product and divides the processes into value adding (VA) or non-value adding (NVA) groups. This helps to navigate through issues in inventory and estimation of manufacturing lead-time (Rohac and Januska, 2015). Indrawati and Ridwansyah (2015) focuses on improvements of product quality and organizational productivity through stages of definition, measurement, analysis, improvement, and control (DMAIC).

Shah and Ward (2007) identified misconceptions and semantic misinterpretations around LM which they aimed to provide clarity on. The findings were that lean production practices were able to achieve competitive advantage and were well accepted by practitioners, professionals, and academics. However, there exists misinterpretations due to a lack of common definitions between different industries or professionals. The different principles of lean have limitations that do not allow for the full exploitation of them by industries. Schonberger (2019) in a study suggested that organizations that have implemented LM did not perform as expected. The study opined those lean principles have not adequately yielded the desired results, especially in inventory management. The study noted that the need for inventory management was increasing with growing demand, and this could increase operational costs for organizations. Reduction of inventory is essential for successful LM and positive customer response (Schonberger, 2019).

4. Additive manufacturing

AM is “a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies” (ASTM, 2021). AM is a growing manufacturing method that is gaining application in several industrial sectors such as aerospace, automotive, construction, architecture, medicine (Al Rashid et al., 2020; Bhatia and Sehgal, 2021; Rasiya et al., 2021). AM has only been in the recent years transitioning from being a prototyping method to product development as customized and low-cost products can be developed (Ngo et al., 2018). AM within the last three decades has evolved to offer the ability to transform manufacturing and logistics processes. Unlike traditional manufacturing methods which are subtractive by nature, where the materials are cut, bent, and joined by welding, soldering, etc., AM builds the material layer by layer on demand thereby reducing material consumption and lead time (Ghobadian et al., 2020; Ngo et al., 2018).

ISO/ASTM 52950 (2021) divides AM into seven (7) subcategories, namely: Vat photopolymerization (VPP), powder bed fusion (PBF), material extrusion (MEX), material jetting (MJT), binder jetting (BJT), directed energy deposition (DED), and sheet lamination (SHL). The main materials that can be used by AM are different metals, polymers, ceramics, composites, biologicals and hybrid materials (Kiran et al., 2018; Tofail et al., 2018). The cost of AM machines is reducing due to the growth of demand and associated technologies (Ngo et al., 2018).

The main processes steps of AM can be grouped as the pre-processing, processing (the actual printing of part) and the post-processing (Groneberg et al., 2022) as shown in Fig. 3.

Fig. 3 shows the main process stages and sub-activities for additively manufactured AM parts. The pre-processing stage includes the concept design, CAD modelling, and design optimization based on defined use requirement and constraints. The digital CAD geometry defines the final component design shape. The embodiment of the part design is optimized based on intended geometry, materials properties, and selected AM subcategory constraints for the intended application. The product optimization iterations is achieved using either finite element method (FEM) or computational fluid dynamic (CFD) numerical simulation of structural response. The definition of the outer envelope and conversion to the slicing phases, toolpaths and process parameters are defined based on design guidelines of the specified AM method. The build simulation considers the build orientation, supporting structures and process parameters. The result of the embodiment design simulation is used to define the actual build process parameters to validate CAE experimental predictions to avoid failures during the printing and product utilization (Rosso et al., 2021). Pre-print simulations enhance the understanding of engineering performance of components prior physical undertakings. The physical printing follows with a readable AM G-coding of the sliced data. For instance, the generated data may include the environmental viable sensor reading and process parameter feedback. These data are useful for analyzing the process behavior and to give process feedback controls (Leary, 2020). The removal, cleaning, inspection, and application of the printed components chronologically follow. Firstly, the printed part is removed, cleaned, and post processed (e.g., machined where necessary). Secondly, inspection of either the metrology data for dimensional stability and proof testing for mechanical response of the component is done to evaluate the reliability and quality. Lastly, the manufactured part can be used for the intended application or reworked (seldom) based on inspection outcome.

AM offers design flexibility to create complex and conformal geometries which are not possible using traditional manufacturing methods (Campbell et al., 2013). Design freedom for complex parts through integrated assembly processes reduce cost, time, and quality issues (Altekin and Bukchin, 2022; Ford and Despeisse, 2016). AM omits tooling and fixtures, thereby reducing manufacturing cost (Altekin and Bukchin, 2022). This beneficially eliminates switch over costs as parts

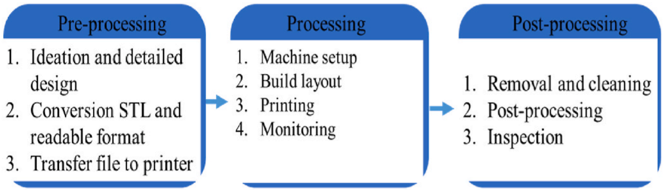

Fig. 3. Representation of process steps for additive manufacturing.

are generated from a 3D model and built with corresponding machine systems. AM allow to reduce manufacturing time, costs, part weight, part counts and scrap through optimization, customization and combined build of multiple identical and non-identical parts (part consolidation) (Campbell et al., 2013), while also having improved resource efficiency and better lead-time which reduces lifetime costs (Altekin and Bukchin, 2022; General Electric, 2018). Repairs, remanufacturing, and refurbishments capability through reverse engineering to redesign parts for AM extends the life cycle of the products and materials. This improves socio-economic factors like improved the life cycle cost and product circularity (Ford and Despeisse, 2016). A model-based estimation shows that the adoption of AM can potentially decrease 5% of lifecycle costs, energy consumption and carbon dioxide (CO_2) emissions. An exemplary estimation indicated AM could save up to $ 593 billion, 9.30 EJ and 525.5 Mt CO_2 equivalent respectively by 2025 (Gebler et al., 2014). AM offers the capability of improving transportation related emissions by enabling localized manufacturing (Javaid et al., 2021; Kellens et al., 2017). AM offers economic advantages for parts in small to medium batch production especially metal parts. The virtual process planning and building of parts using AM reduces materials wastage, supply risks with swift and on-demand manufacturing.

The different AM categories have inherent challenges that needs improvements to strengthen the utilization for the offered advantages to propel continuous industrial adoption. Limited expertise of current designers and technical professionals creates gap in the full uptake of AM. Lack of standardization for new materials and certification of AM parts potentially deter a wider industrial application (Ford and Despeisse, 2016). Mandatory support structures and post-processing usually requires additional time and creates additional costs. Speed is often criticized as slow and the machinery costs especially in metal AM system often as high (Pérez et al., 2020). The continuous development of advanced machines with higher energy sources, multiple systems, increase build volume is expected to decrease costs (Duda and Raghavan, 2016; Khorasani et al., 2020).

PBF and DED are the most widely used AM technologies for metal AM as they can build complex and fully dense products (Nyamekye et al., 2020). Extant literature has provided several methods to use AM. Metal AM applications may be able to save material through recycling and reuse technologies, as well as redesigning and repairing different components in the life cycle of a metal product (Daraban et al., 2019). Some of the sustainability benefits of metal AM includes material and energy efficiency, better product life (through life cycle thinking), and stronger value chains. Lifecycle assessment (LCA) may also be used to understand environmental impacts further by integrating environmental impact analysis of a product from material extraction to the end of life, including service (maintenance and repair), production, transportation, etc. Additionally, special attention should be given to ensure that non-toxic and reusable (or alternate) materials should be used, with improved support structures, and optimally designed parts with reduced waste (Daraban et al., 2019). AM also supports the transition from a manufacturer-centric to a consumer-centric supply chain. Bogers et al. (2016) investigate how value can be captured and appropriated by using AM from the consumer perspective by using the novelty, lock-In, complementarities, and efficiency (NICE) design system (Zott and Amit, 2010). Implementing AM and LM gives rise to more centralized supply and consumer-centric business models, and equips consumers with the ability to add value to the product as they may be personalized and printed on demand (Bogers et al., 2016). In general, activities closer to the end user (reuse, remanufacture) have a less negative environmental impact than those further away from the end user (recycle, refurbish) and hence increases SM (Wits et al., 2016). AM enables maintenance, repair, and overhaul (MRO) capabilities in a series of steps including: (i) CAD model provided by the original equipment manufacturer, which is downloaded from a digital cloud and obtained by the end-user, (ii) printing the CAD file, and (iii) replacement (MRO) of the parts. These steps can be optimized for the end-user by optimally designing the part before printing by (i) adapting and consolidating the parts, and (ii) implementing new applications (Wits et al., 2016).

5. Simulation-driven DfAM

Design for additive manufacturing (DfAM) refers to the designing of products in the most optimal way for easy manufacturing using AM (Wiberg et al., 2019). DfAM aids to manage the product design geometry and topology complexities for the ease of AM. DfAM guides three main aspects of AM including the system design, part design and process design. A seamless digital thread can be used to integrate all three aspects of AM systems referred to as simulation driven DfAM (Nyamekye et al., 2020). The use of digital tools in accordance with DfAM guidelines help create optimized new design as well redesigned exiting products which can omit non-performing product components. Simulation-driven DfAM can the used to optimize the different aspects of AM product design as shown in Table 4.

As it can be seen from Table 4, the component selection and design problem and characteristics are first developed. It is followed by the part design which includes the development of the initial design, which is analyzed, after which the support structures are created keeping the build time and cost in consideration. Finally, the print is simulated as part of the process design step before manufacturing the product. The support structures, an unavoidable non valued added component in AM (Groneberg et al., 2022) can be minimized with the right product design optimization.

Adoption of AM with the right use of DfAM has the capability to increase value for the customers with increased ecological, economic and experience (E3) performance (Campbell et al., 2013). AM parts increases value by means of lighter weight, complex designs which decreases energy consumptions, material waste and emissions reduction throughout the lifetime. The economic value can be added through smaller batch sizes and highly customizable products. Customization potentially increases the ecological, economy, and experience values and offer product differentiation (e.g., in terms of functionality, aesthetics, user-fit, etc.) in competitive stands (Campbell et al., 2013). By reducing the number of parts required and the possibility of individualized parts, lightweight and efficient product designs are possible (Wiberg et al., 2019). With less waste material and more lightweight and efficient parts and products, using simulation-driven DfAM with constant improvement and analysis ecological value can be added. It is also possible to minimize support structures and smoothen of the final product through simulation, and material properties may be tailored for different solutions (Wiberg et al., 2019). Estimating the build time is crucial to predict the cost of manufacturing, and their intensive study concluded that the cost models of each AM technology used is comparable (Costabile et al., 2016).

Table 4

DfAM workflow based on simulation (Leutenecker-Twelsiek et al., 2016; Wiberg et al., 2019).

Component design	Chose component for AM
	Define design problem
Part design	Initial CAD model using DfAM rules Define material, load cases, optimization goals Simulation and validation of design Design interpretation and analysis Define print parameters, plan build layout, generate supports, simulate the print Fine tune using DfAM where necessary
Process design	Analysis of support structure Select building parameters Validate build time and cost
Manufacturing of product	Printing of the product

6. Case studies

6.1. *Consumer product: Impact Footwear customizable flip flop*

A startup company, “Impact Footwear” created an innovative digital business model for customizable slippers. The business model of the company provides a cloud-based platform shop to customers with the ability to either select preset slippers or customize them. The cloud-based platform enables the software and hardware to remotely respond to orders. This minimizes human interaction, reduces operational costs, and improve design efficiency. The company developed the idea to a mass-customizable product with 30 design variables in 12 months using nTopology software. The software, nTopCL and nTop of nTopology allow a swift respond to request, an iterative product design and deployment for manufacturing. The software performs iterations of input model to create complex and customized lattice (foam-like) structure for the soles. A plastic based EOS PBF machine system is used to manufacture the preferred designs on-demand. This improves design efficiency, enhances operational costs and customer satisfaction. The slippers are printed from dyed thermoplastic elastomer (TPE) and vapor smoothened using Dye Mansion vaporfuse. Post-processing is done to enhance functional properties, surface quality, and reduce bacteria growth on the footwear (Amt Technologies, n.d.) The Impact F1 Flip Flop with its design features are shown in Fig. 4.

Fig. 4 shows that the different layers of the flip flop are distinctively designed. The Impact F1 Flip Flop has several characteristics and features which give it a competitive edge over flip flops that are made traditionally. In addition to customizable design, the consumer may select their preferred options of visual design, functionality, comfort, grip, and color from the product characteristics shown in Table 5.

As it can be seen from Table 5, the design characteristics are variable and can be chosen based on the preference of customers. Customers can make selections in the design and patterns of the toe, arch, heel, insoles, midsole, traction of the outsole, in addition to color, size and labels. The cloud-based platform and AM offer the benefit of lean with more efficient, streamlined, on-demand manufacturing, reduced inventory, maintenance cost, etc. which minimizes total cost of ownership. The ability for a complete cloud-based solution allows the start-up to concentrate on other aspects such as quality control and marketing while saving time and operational costs.

Fig. 5 shows the cloud-based steps of the purchase order process.

It can be concluded from Fig. 5 that the supply chain processes for the whole process chain is relatively simple. Prospective customers effortlessly customize their product, and the system creates their product. The order stores the product details on the organizations cloud. After placing the order, the flip flop is printed, post processed, packaged, and shipped to the customer.

6.2. *Machine tool: Preziosa Francesco SRL robotic press brake machine gripper*

Fig. 4. Impact F1 flip flop (DeMerit, 2020).

Table 5
Impact F1 Flip Flop characteristics (DeMerit, 2020).

Impact F1 Flip Flop
Upper strap made from recycled material which is changeable to provide different styles
Water resistant in-sole with improved grip and traction options for the customer
Lab designed lattice structures to provide comfort and improved performance
One of a kind custom lattice designed midsole exterior
Outsole patterns with different traction and comfort options
Three individually designed and distinct midsole regions with different compression zones

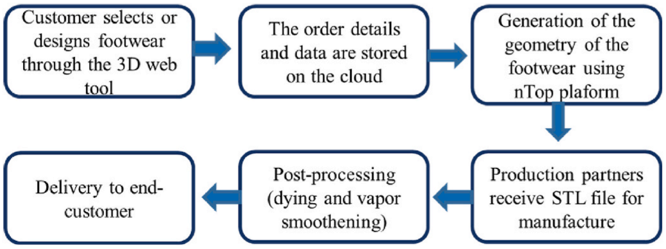

Fig. 5. Cloud-based process of Impact Footwear adapted from (DeMerit, 2020).

Preziosa Francesco SRL specializes in robotic cell and an automated break press brake bending machines which bends sheet metal by clamping the workpiece between a dye and a punch (Fournier and Fournier, 1989). Grippers are devices used to hold objects that are moved by a robot. For different applications, models, and parts, different grippers should be used (Sharma, 2015). The grippers used initially were too slow to manufacture, slippery and not agile. Preziosa Francesco SRL partnered with AM design and consultant ‘Add-it’ to redesign a robotic ends effector’s gripper, an integral part the bending machines. Fig. 6 shows the gripper used for the bending processes by Preziosa Francesco SRL.

As it can be seen from Fig. 6, the grippers require high precision and technical performance for the bending processes. Grippers of different designs are required for different sheet metal bending processes. By using topology optimization and laser-based powder bed fusion (L-PBF), customized grippers were manufactured. Topology optimization is an approach that provides the optimal design for a part within certain boundary conditions to enhance the product performance (Merulla et al., 2019). The material used was 17-4 PH stainless steel which has high strength, hardness, and corrosion resistance. The required gripping force or traction was obtained after iterations, and the final lightweight design was ready in four days. Fig. 7 illustrates the original design, the four different design iterations and the final optimized part designed.

It can be observed from Fig. 7 that there have been four iterations from V1 to V4 to obtain the final optimized part using digital tools in conformity to simulation-driven DfAM guidelines. Add-it used their built-in topology optimization software was to obtain the optimized

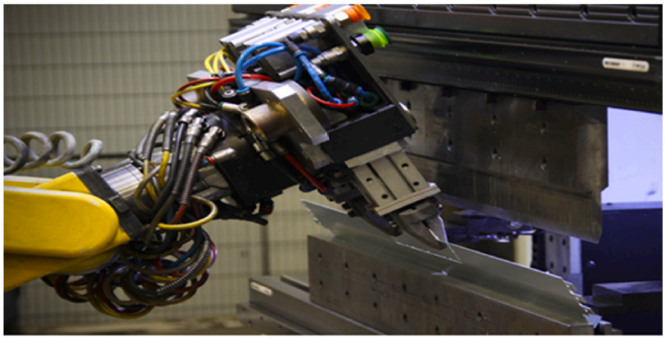

Fig. 6. Robotic end effector’s gripper (nTopology, 2021)

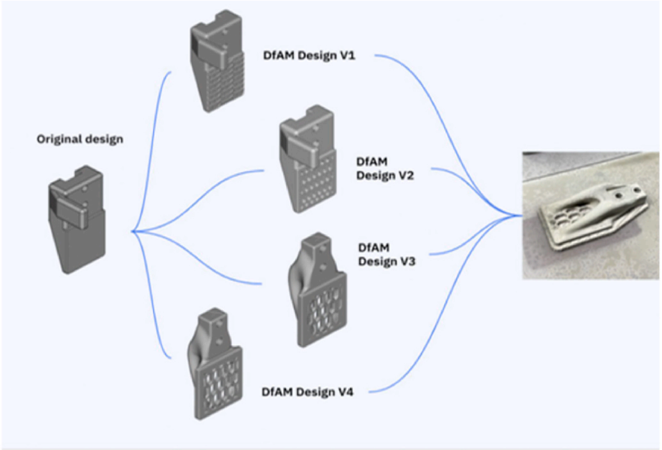

Fig. 7. Illustration of the original and iterative design optimization (nTopology, 2021).

geometry. The goal was to create the product with similar stiffness, grip force, weight, and smaller product footprint. Multiple designs were created with different iterations to test the stress under different boundary conditions.

Fig. 8 shows two that there were two separate tests performed under different density threshold values. It can be seen that the higher threshold offers a more optimized design with reduced material requirement and hence more lightweight. The redesigned optimized model yielded satisfactory results and an enhanced time to market. In addition to weighing 32–40% less than the original model, there was a cost savings of 35% in comparison to purchasing the grippers from other suppliers who were traditionally manufacturing them. The final product was ready in four days, including the design, optimization, and printing which was expected to take more than two weeks initially.

7. Results and discussion

The presented cases on AM show the capability to increase raw material circularity through redesign, repairs, or refurbishment. This was achieved through redesigned industrial system (e.g., AM) and business model (e.g., cloud-based solutions). The use of PBF and cloud-based platform offered a means to increased value, reduced resource consumption and waste minimization. AM when effectively adopted enables a more sustainable digital transformation and offers competitive advantage in the markets. An organization can achieve competitive sustainable advantages by prioritizing individual elements or integrating the different factors of LM with AM (Shah and Ward, 2007). An integrated LM and AM strategy solves several issues related to sustainability and may provide companies with a competitive advantage, which could enable them to have profitable value propositions in the market.

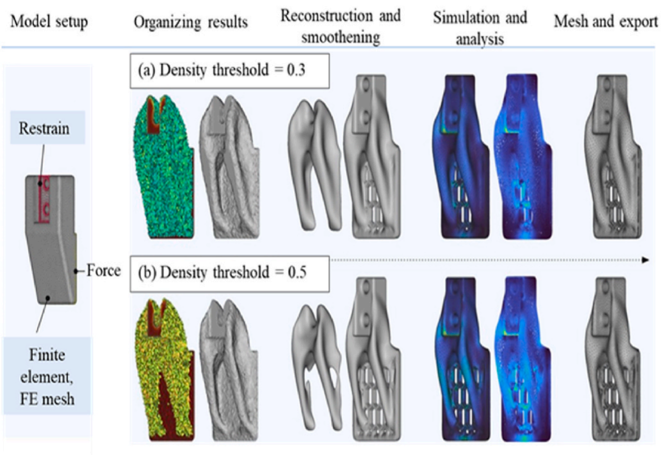

Fig. 8. Simulation-driven optimization workflow density threshold (a) 0.3 and 0.5. Adapted from (nTopology, 2021).

7.1. *Convergence of LM and AM from sustainability aspects*

The authors provide evidence to support that AM correlates to LM, and that industrial adoption of LM and AM can prove beneficial. The integration of AM and LM provides several opportunities to enhance resource and cost efficiency and to reduce waste creation. AM adds value to the organization while being economically, socially, and environmentally responsible. The convergence of AM and LM improves the space utilized, material consumption, created wastes and emissions via digitalization. AM and LM when effectively combined can aid in the identification and management of associated costs, idleness, and other benefits from the use emerging innovations and associated technologies. In summary, this article identifies keyways by which LM and AM can be used to enhance modernization, improve cost, time, space, waste, and emission reduction as Fig. 9 shows.

As it can be seen from Fig. 9, the combination of LM and AM can potentially enhance space utilization from the point of reduced inventory, omission of tools and fixtures. The added values at the various levels promotes resource efficiency towards more ecological-efficient and economic operations. Both LM and AM also save time through reduced transportation, on-demand, and localized swift manufacturing. Digital tools can equip manufacturers to optimize the designs with quicker iteration tools. Finally, overall cost may be reduced through mass customization, reduced manufacturing steps, reduced cost for delivery and part consolidation.

7.2. *Industrial relevance and novelty of the study*

Fig. 10 shows the positive impacts of integrating the LM business model into core manufacturing processes (i.e., AM) for an organization.

As Fig. 10 shows, the convergence of AM and LM provides sustainable benefits for the three pillars of sustainability: the environment, the economy, and the society. Reduction of waste and emissions are the most important characteristics for environmental sustainability from the LM and AM perspective. In addition, reduction of operation and maintenance costs, smart supply chains, emerging technology and business are some of the societal and economic benefits.

From the perspective of LM and AM, the authors highlight the capabilities of AM to enhance lean practices in manufacturing industries. Studies show that smart factories minimizes waste, pollution generation (King and Lenox, 2001), and improve operational efficiency, productiveness and sustainability aspects (Godina et al., 2020; Smelov et al., 2014). LM enable such reductions via the offered benefits of omitted non-valuable time consuming activities whereas AM enable customization, reduced time to market, real time monitoring and optimizing of manufacturing. The integration of leanness into industrial operation continues to grow due to the environmental, economic, and social impacts. SM offer ways to quality improvement, waste reduction, material efficiency (reduction and recycling) and improved process efficiency. Achieving such goals also contribute to the one of the most important goals of improving customer satisfaction. Non-value-added activities such as the consumption of energy, fuel and water is also considered waste in the LM.

AM helps reduce such consumption with omission of process fluids, localized manufacturing, and lightweight parts. For example, less transport reduces operational expenses and CO_2 emissions, and hence shows the integration of LM and AM towards the achievement of waste reduction and process efficiency. Excess inventory extends communication and lead times. AM offers the possibility of integrated systems interaction, swift iterations and manufacturing, real time monitoring

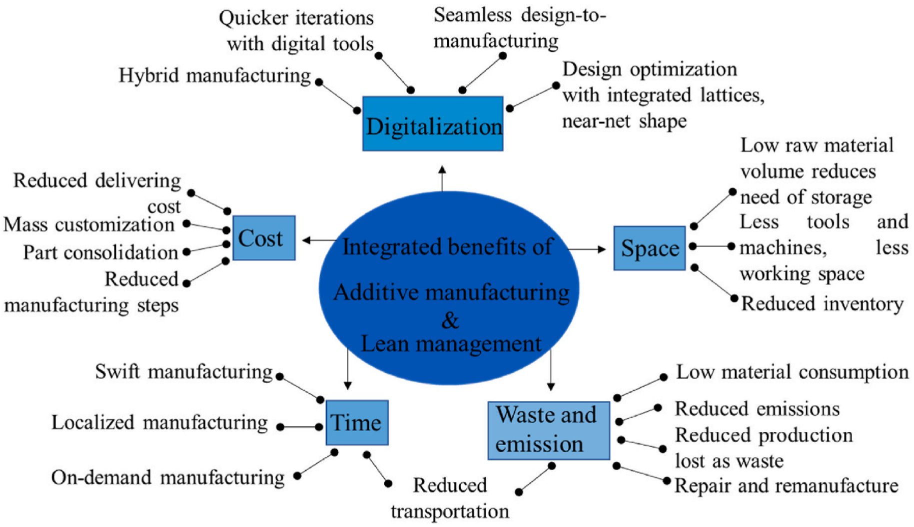

Fig. 9. Representation of the potential benefits of an integrated LM and AM.

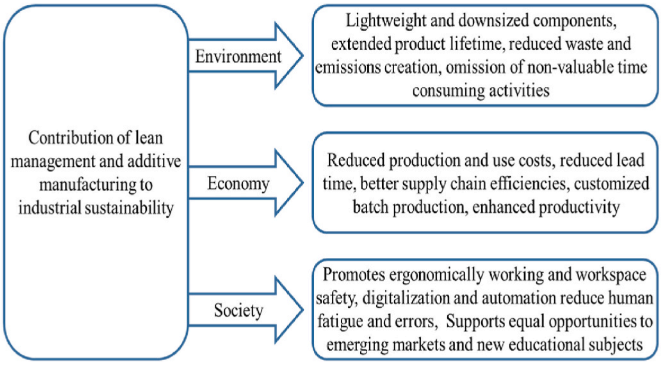

Fig. 10. Industrial sustainability aspects of the convergence of AM and LM (Ghobadian et al., 2020; Javaid et al., 2021; Tonelli et al., 2013).

and potential to real time manufacturing (Godina et al., 2020; Smelov et al., 2014) to reduce lead time, waste and costs. These offered benefits enhance leanness in production for material efficiency and improved sustainability (Chen and Lin, 2017; Ghobadian et al., 2020). Other studies (Carvalho et al., 2011; Garza-Reyes et al., 2014) have shown that the integration of LM and AM systems provided effective and beneficial improvements in inventory levels, processes, transportation, production times, financial and environmental efficiencies. Table 6 shows the contribution of LM and AM to sustainability and the convergence of the two.

As it can be seen from Table 6, both LM and AM provide derived benefits when used together, providing an organization with opportunities to increase growth, reduce costs, increase production efficiency and an improved supply chain, in addition to being more environmentally friendly. The elimination of waste can be obtained by LM and AM, as LM aims to eliminate waste and AM if used optimally has no waste. Time to market is critical for organizations and the integration of AM and LM can help organizations be more receptive to their clients while also keeping their inventory levels in check. Additionally, the life cycle cost effectiveness is improved by AM and LM as products are made optimally, through simulation-driven DfAM and the best integrating LM factors. On-demand manufacturing also reduces the need for excess stock and inventory, which would lead to reduced transportation from suppliers and on different levels within the supply chain. Down-time reduction is not applicable for LM, however, by incorporating AM with LM, the down-time reduction can be enhanced and operational practices within the organization related to production can become more efficient.

Table 6
Contribution of derived benefits of lean and AM to sustainability.

Derived benefits	LM	AM
Elimination of waste	Yes	Yes
Time efficiency	Yes	Yes
Inventory reduction	Yes	Yes
Down-time reduction	Not applicable/can be enhanced with AM	Yes
Life cycle cost effectiveness	Yes	Yes
On-demand manufacturing	Yes	Yes
Transportation reduction	Yes	Yes

The main findings of this study are the potentials of integration of LM and AM to unleash hidden values for companies, which offer higher supply chain resilience and omission of waste in the value chain, a rationalized digital inventory and logistics reducing the total cost of ownership and lead time, and improved customer satisfaction with on-demand manufacturing, reduced lead time, and spare parts beyond the service life of the product.

8. Conclusions

The analyzed LM and AM concepts based on the collected literature data and case studies formed the basis of this study. The use of digital tools for predictive AM process flow allows to achieve several of the waste saving aims of LM capable of enhancing production and processing efficiency. Waste is minimized with the combined benefits of reduced production losses as companies have an option to digital inventory thereby reducing the tendency of stocking outdated products. Furthermore, AM allow efficient time utilization as companies have the option of localizing manufacturing which subsequently reduces the need of transportation as well the waiting time via swift designing and manufacturing. LM and AM can enhance cost efficiency by way of reducing manufacturing steps, mass customization, integrated functions and reduction of non-valve adding steps which otherwise are complementary to conventional manufacturing supply chains.

This study demonstrates the value of simulation-driven DfAM and digitalization in terms of manufacturing time, space, wastes and emission for improved productivity and leanness. The identified ways by which AM addresses production waste should guide industrial AM adopters to actively redesign existing products for AM and to design new components with emphasis on DfAM guidelines. The findings of this study can also aid manufacturing companies decide whether to invest in

AM machine for in-house production, to outsource production or use a mixture of both. AM can create better performing designs as single or combination of lattice, topology, ribbing, etc., which are not achievable with any of the CM methods, and as well shorten time to market. The quicker steps of creating reliable optimized product designs from CAD models with fewer iterations of the design reduces the design phase energy consumption and lead-time. AM is shown to shorten physical inventory with digital inventory, quicken the physical building of the optimized design through, digital process planning, validation, and batching. The omission of tooling and fixtures in AM reduces company costs in both homogenous and heterogeneous batching. Downtime in operations and halting of production due to unavailability of the suitable tools and fixtures as characterized in CM is potentially eliminated. AM has the potential to reduce the process steps, production time and resource consumption depending on the AM subcategory used. The adoption of AM to mainstream manufacturing continue to develop as further improvement are required to create functional parts. This study identified ways by which companies can enhance productivity with digital inventory to enhance operational leanness. More efforts from academic and industrial researchers will be needed to identify and communicate the best ways by which LM and AM can support growth along the digital transformation to curtail the current gaps in literature.

One of the limitations of the study lies in the data collection where only specific keywords were used for the search. By focusing only on the keywords “lean manufacturing”, “lean management”, “additive manufacturing” and “3D printing”, the authors understand that there may be several other relevant keywords, and hence publications that cover the full essence of the topic of the research but were not included. However, the authors believe that these were the most relevant keywords that relate to the essence of the study. Another limitation related to the data collection is that the main publications for the analysis were chosen from the year 2012 onwards, and there may have been several studies prior to 2012 which were relevant for the study, specifically related to LM and lean manufacturing. Finally, there authors acknowledge the semantic misinterpretations and misunderstandings between different fields of scientific research in technology and business and hence took the best effort to bridge the gap of this issue.

Since AM is still a growing technology, there are several capabilities of the technologies that may have not yet been realized. There are several further studies that can be considered while conducting research. For example, the role of sustainable business models for an integrated LM and AM strategy could equip companies with a tool or framework that may be used in their operational management, which may be tested empirically through quantitative research tools. Another area to address can include the different ecosystem actors, the role of AI, and commercialization processes for an integrative LM and AM strategy. The authors urge future researchers to address these topics to enable more circular industrial practices.

Author contribution

Rohit Lakshmanan: Conceptualization, Data curation, Investigation, Writing – original draft, review, and editing, Visualization. **Patricia Nyamekye.** Conceptualization, Data curation, Investigation, Writing – Original draft, review, and editing. **Vile-Matti Virolainen.** Funding acquisition, supervision, reviewing. **Heidi Piili.** Conceptualization, supervision, reviewing.

Funding

This study was funded by the Analytics-based Management for Business and Manufacturing Industry (AMBI) platform at LUT University.

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.

Data availability

Data will be made available on request.

Acknowledgements

The authors wish to acknowledge the AMBI platform for supporting this interdisciplinary research among the School of Energy Systems and Laser Laboratory at LUT. The authors also acknowledge the Department of Mechanical Engineering (Faculty of Technology) at Turku University (UTU) for their support and contribution to this study.

References

Abualfaraa, W.A., Salonitis, K., Al-Ashaab, A., 2017. Improving sustainability of manufacturing systems through integrated sustainable value stream mapping tool - conceptual framework. Advances in Transdisciplinary Engineering 6, 371–376. https://doi.org/10.3233/978-1-61499-792-4-371.

Agarwal, R., Helfat, C.E., 2009. Strategic renewal of organizations. Organ. Sci. 20 (2), 281–293. https://doi.org/10.1287/orsc.1090.0423.

Ahi, P., Searcy, C., 2013. A comparative literature analysis of definitions for green and sustainable supply chain management. J. Clean. Prod. 52, 329–341. https://doi.org/10.1016/j.jclepro.2013.02.018.

Al Rashid, A., Khan, S.A., Al-Ghamdi S, G., Koç, M., 2020. Additive manufacturing: technology, applications, markets, and opportunities for the built environment. Autom. ConStruct. 118, 103268 https://doi.org/10.1016/J.AUTCON.2020.103268.

Aljinović, A., Gjeldum, N., Bilić, B., Mladineo, M., 2021. Optimization of industry 4.0 implementation selection process towards enhancement of a manual assembly line. Energies 15 (1), 30. https://doi.org/10.3390/en15010030.

Altekin, F.T., Bukchin, Y., 2022. A multi-objective optimization approach for exploring the cost and makespan trade-off in additive manufacturing. Eur. J. Oper. Res. 301 (1), 235–253. https://doi.org/10.1016/j.ejor.2021.10.020.

Amt Technologies. (n.d.). Patented Chemical Vapor Smoothing Systems. https://amtechnologies.com/vapor-smoothing/.

Aradhye, A.S., Kallurkar, S.P., 2014. A case study of just-in-time system in service industry. Procedia Eng. 97, 2232–2237. https://doi.org/10.1016/J.PROENG.2014.12.467.

ASTM, 2021. ISO/ASTM 52900:2021 - Additive manufacturing - General principles - Overview of data processing. January ICS. https://www.iso.org/standard/76830.html.

Bag, S., Yadav, G., Wood, L.C., Dhamija, P., Joshi, S., 2020. Industry 4.0 and the circular economy: resource melioration in logistics. Resour. Pol. 68 https://doi.org/10.1016/j.resourpol.2020.101776.

Barney, J., 1991. Firm resources and sustained competitive advantage. J. Manag. 17 (1), 99–120.

Barr, P.S., Stimpert, J.L., Huff, A.S., 1992. Cognitive change, strategic action, and organizational renewal. Strat. Manag. J. 13 (S1), 15–36. https://doi.org/10.1002/SMJ.4250131004.

Bhatia, A., Sehgal, A.K., 2021. Additive manufacturing materials, methods and applications: a review. May Mater. Today Proc.. https://doi.org/10.1016/J.MATPR.2021.04.379.

Bittencourt, V., Saldanha, F., Alves, A.C., Leão, C.P., 2019. Contributions of lean thinking principles to foster industry 4.0 and sustainable development goals. In: Lean Engineering for Global Development. Springer International Publishing, pp. 129–159. https://doi.org/10.1007/978-3-030-13515-7_5.

Boer, J. den, Lambrechts, W., Krikke, H., 2020. Additive manufacturing in military and humanitarian missions: advantages and challenges in the spare parts supply chain. J. Clean. Prod. 257, 120301 https://doi.org/10.1016/j.jclepro.2020.120301.

Bogers, M., Hadar, R., Bilberg, A., 2016. Additive manufacturing for consumer-centric business models: implications for supply chains in consumer goods manufacturing. Technol. Forecast. Soc. Change 102, 225–239. https://doi.org/10.1016/j.techfore.2015.07.024.

Brundtland, G., 1987. Report of the world commission on environment and development: our common future towards sustainable development 2. Part II. Common Challenge Populate. Human Res. 4 (1), 1.

Campbell, I., Jee, H., Kim, Y., 2013. Adding product value through additive manufacturing. Int. Conf. Eng. Design. 259–268.

Carvalho, H., Duarte, S., Machado, V.C., 2011. Lean, agile, resilient and green: divergencies and synergies. Int. J. Lean Six Sigma 2 (2), 151–179. https://doi.org/10.1108/20401461111135037.

Chen, T., Lin, Y.C., 2017. Feasibility evaluation and optimization of a smart manufacturing system based on 3D printing: a review. Int. J. Intell. Syst. 32 (4) https://doi.org/10.1002/int.21866.

Chiarini, A., 2013. The main methods of lean organization: kanban, cellular manufacturing, SMED and TPM. In: Lean Organization: from the Tools of the Toyota Production System to Lean Office, pp. 81–116. https://doi.org/10.1007/978-88-470-2510-3_6.

Christopher, M., Ryals, L.J., 2014. The supply chain becomes the demand chain. J. Bus. Logist. 35 (1), 29–35. https://doi.org/10.1111/jbl.12037.

Chronéer, D., Wallström, P., 2016. Exploring waste and value in a lean context. Int. J. Bus. Manag. 11 (10), p282. https://doi.org/10.5539/IJBM.V11N10P282.

Costabile, G., Fera, M., Fruggiero, F., Lambiase, A., Pham, D., 2016. Cost models of additive manufacturing: a literature review. Int. J. Ind. Eng. Comput. https://doi.org/10.5267/j.ijiec.2016.9.001.

Daraban, A.E.O., Negrea, C.S., Artimon, F.G.P., Angelescu, D., Popan, G., Gheorghe, S.I., Gheorghe, M., 2019. A deep look at metal additive manufacturing recycling and use tools for sustainability performance. Sustainability 11 (19), 5494. https://doi.org/10.3390/su11195494. MDPI AG.

DeMerit, C., 2020. Case Study: Impact Footwear Br*ings to Market Customizable Flip Flops | nTopology*. November. Case Studies.

Duda, T., Raghavan, L.V., 2016. 3D metal printing technology. IFAC-PapersOnLine 49 (29), 103–110. https://doi.org/10.1016/J.IFACOL.2016.11.111.

Filip, F.C., Marascu-Klein, V., 2015. The 5S lean method as a tool of industrial management performances. IOP Conf. Ser. Mater. Sci. Eng. 95 (1) https://doi.org/10.1088/1757-899X/95/1/012127.

Ford, S., Despeisse, M., 2016. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. J. Clean. Prod. 137, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150.

Fournier, R., Fournier, S., 1989. Sheet Metal Handbook.

Galati, F., Bigliardi, B., 2019. Industry 4.0: emerging themes and future research avenues using a text mining approach. In: Computers in Industry, vol. 109, pp. 100–113. https://doi.org/10.1016/j.compind.2019.04.018.

Galpin, T., Whittington, J.L., Bell, G., 2015. Is your sustainability strategy sustainable? Creating a culture of sustainability, 1. In: Corporate Governance International Journal of Business in Society, 15, pp. 1–17. https://doi.org/10.1108/CG-01-2013-0004.

Garza-Reyes, J.A., Winck Jacques, G., Lim, M.K., Kumar, V., Rocha-Lona, L., 2014. Lean and green - synergies, differences, limitations, and the need for six sigma. IFIP Adv. Inf. Commun. Technol. 439 (PART 2), 71–81. https://doi.org/10.1007/978-3-662-44736-9_9.

Gebisa, A.W., Lemu, H.G., 2017. Design for manufacturing to design for Additive Manufacturing: analysis of implications for design optimality and product sustainability. Procedia Manuf. 13, 724–731. https://doi.org/10.1016/j.promfg.2017.09.120.

Gebler, M., Schoot Uiterkamp, A.J.M., Visser, C., 2014. A global sustainability perspective on 3D printing technologies. Energy Pol. https://doi.org/10.1016/j.enpol.2014.08.033.

General Electric, 2018. The 3D-Printed Age: Why This Futuristic Ohio Factory Is Proving Mark Twain Wrong.

Ghobadian, A., Talavera, I., Bhattacharya, A., Kumar, V., Garza-Reyes, J.A., O'Regan, N., 2020. Examining legitimatisation of additive manufacturing in the interplay between innovation, lean manufacturing and sustainability. Int. J. Prod. Econ. 219, 457–468. https://doi.org/10.1016/j.ijpe.2018.06.001.

Godina, R., Ribeiro, I., Matos, F., Ferreira, B.T., Carvalho, H., Peças, P., 2020. Impact assessment of additive manufacturing on sustainable business models in industry 4.0 context. Sustainability 12 (17). https://doi.org/10.3390/su12177066.

Grasso, M., Colosimo, B.M., 2017. Process defects and in situ monitoring methods in metal powder bed fusion: a review. In: Measurement Science and Technology, vol. 28. Institute of Physics Publishing. https://doi.org/10.1088/1361-6501/aa5c4f. Issue 4.

Groneberg, H., Horstkotte, R., Pruemmer, M., Bergs, T., Döpper, F., 2022. Concept for the reduction of non-value-adding operations in laser powder bed fusion (L-PBF). Procedia CIRP 107, 344–349. https://doi.org/10.1016/J.PROCIR.2022.04.056.

Helfat, C.E., Martin, J.A., 2015. Dynamic managerial capabilities: review and assessment of managerial impact on strategic change. J. Manag. 41 (5), 1281–1312. https://doi.org/10.1177/0149206314561301.

Hines, P., Holwe, M., Rich, N., 2004. Learning to evolve: a review of contemporary lean thinking. Int. J. Oper. Prod. Manag. 24 (10), 994–1011. https://doi.org/10.1108/01443570410558049.

Indrawati, S., Ridwansyah, M., 2015. Manufacturing continuous improvement using lean six sigma: an iron ores industry case application. Procedia Manuf. 4, 528–534. https://doi.org/10.1016/J.PROMFG.2015.11.072.

International Organization for Standardization, 2021. Sustainability, Sustainable Development and Social Responsibility.

Javaid, M., Haleem, A., Singh, R.P., Suman, R., Rab, S., 2021. Role of Additive Manufacturing applications towards environmental sustainability. Adv. Indust. Eng. Poly Res. https://doi.org/10.1016/J.AIEPR.2021.07.005.

Jbira, K., Hlyal, M., El Alami, J., 2020. Integration of Lean management for the growth of Green manufacturing. IOP Conf. Ser. Mater. Sci. Eng. 827 (1) https://doi.org/10.1088/1757-899X/827/1/012027.

Kellens, K., Baumers, M., Gutowski, T.G., Flanagan, W., Lifset, R., Duflou, J.R., 2017. Environmental dimensions of additive manufacturing: mapping application domains and their environmental implications. J. Ind. Ecol. 21, S49–S68. https://doi.org/10.1111/jiec.12629.

Khorasani, A.M., Gibson, I., Veetil, J.K., Ghasemi, A.H., 2020. A review of technological improvements in laser-based powder bed fusion of metal printers. Int. J. Adv. Manuf. Technol. 108 (1–2), 191–209. https://doi.org/10.1007/s00170-020-05361-3.

King, A.A., Lenox, M.J., 2001. Lean and green? An empirical examination of the relationship between lean production and environmental performance. Prod. Oper. Manag. 10 (3), 244–256. https://doi.org/10.1111/J.1937-5956.2001.TB00373.X.

Kiran, A.S.K., Veluru, J.B., Merum, S., Radhamani, A.V., Doble, M., Kumar, T.S.S., Ramakrishna, S., 2018. Additive manufacturing technologies: an overview of challenges and perspective of using electrospraying. Nanocomposites 4 (4), 190–214. https://doi.org/10.1080/20550324.2018.1558499.

Krafick, J.F., 1988. Triumph of the lean production system. Sloan Manag. Rev. 30 (1), 41. https://edisciplinas.usp.br/pluginfile.php/5373958/mod_resource/content/4/krafcik_TEXTO_INTEGRAL.pdf.

Kumar, P., Bhadu, J., Singh, D., Bhamu, J., 2021. Integration between lean, six sigma and industry 4.0 technologies. Int. J. Six Sigma Compet. Advant. 13 (1–3), 19–37. https://doi.org/10.1504/IJSSCA.2021.120224.

Leary, M., 2020. Digital Design for AM. In *Design for Additive Manufacturing*. Elsevier, pp. 33–90. https://doi.org/10.1016/b978-0-12-816721-2.00003-8.

Lermen, F.H., de Moura, P.K., Bertoni, V.B., Graciano, P., Tortorella, G.L., 2023. Does maturity level influence the use of Agile UX methods by digital startups? Evaluating design thinking, lean startup, and lean user experience. Inf. Software Technol. 154, 107107 https://doi.org/10.1016/J.INFSOF.2022.107107.

Leutenecker-Twelsiek, B., Klahn, C., Meboldt, M., 2016. Considering Part Orientation in design for additive manufacturing. Procedia CIRP 50, 408–413. https://doi.org/10.1016/J.PROCIR.2016.05.016.

Merulla, A., Gatto, A., Bassoli, E., Munteanu, S.I., Gheorghiu, B., Pop, M.A., Bedo, T., Munteanu, D., 2019. Weight reduction by topology optimization of an engine subframe mount, designed for additive manufacturing production. Mater. Today Proc. 19, 1014–1018. https://doi.org/10.1016/J.MATPR.2019.08.015.

Miller, G., Pawloski, J., Standridge, C., 2010. A case study of lean, sustainable manufacturing. J. Ind. Eng. Manag. 3 (1), 11–32. https://doi.org/10.3926/jiem.2010.v3n1.p11-32.

Moldavska, A., Welo, T., 2017. The concept of sustainable manufacturing and its definitions: a content-analysis based literature review. J. Clean. Prod. 166, 744–755. https://doi.org/10.1016/j.jclepro.2017.08.006.

Ngo, T.D., Kashani, A., Imbalzano, G., Nguyen, K.T.Q., Hui, D., 2018. Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. Compos. B Eng. 143, 172–196. https://doi.org/10.1016/j.compositesb.2018.02.012nTopology (2021). *Agile Industrial Robot Grippers with Topology Optimization & Metal 3D Printing.*

Nyamekye, P., Unt, A., Salminen, A., Piili, H., 2020. Integration of simulation driven DfAM and LCC analysis for decision making in L-PBF. Metals 2020 (10), *1179*. https://doi.org/10.3390/MET10091179, 10(9), 1179.

Pavnaskar, S.J., Gershenson, J.K., Jambekar, A.B., 2003. Classification scheme for lean manufacturing tools. Int. J. Prod. Res. 41 (13), 3075–3090. https://doi.org/10.1080/0020754021000049817.

Pérez, M., Carou, D., Rubio, E.M., Teti, R., 2020. Current advances in additive manufacturing. Procedia CIRP 88, 439–444. https://doi.org/10.1016/j.procir.2020.05.076.

Porter, M.E., 1980. Competitive Strategy: Techniques for Analyzing Industries and Competitors. Free Press, New York. https://www.hbs.edu/faculty/Pages/item.aspx?num=195.

Rasiya, G., Shukla, A., Saran, K., 2021. Additive manufacturing-A review. Mater. Today Proc. https://doi.org/10.1016/J.MATPR.2021.05.181.

Rohac, T., Januska, M., 2015. Value stream mapping demonstration on real case study. Procedia Eng. 100 (January), 520–529. https://doi.org/10.1016/J.PROENG.2015.01.399.

Roosen, T.J., Pons, D.J., 2013. Environmentally lean production: the development and incorporation of an environmental impact index into value stream mapping. J. Ind. Eng. 2013, 1–17. https://doi.org/10.1155/2013/298103.

Rosso, S., Uriati, F., Grigolato, L., Meneghello, R., Concheri, G., Savio, G., 2021. An optimization workflow in design for additive manufacturing. Appl. Sci. 11 (6) https://doi.org/10.3390/app11062572.

Schiuma, G., 2009. The challenges of measuring business excellence in the 21st century. Measure Business Excellence. 13 (2) https://doi.org/10.1108/mbe.2009.26713baa.001.

Schonberger, R.J., 2019. The disintegration of lean manufacturing and lean management. Bus. Horiz. 62 (3), 359–371. https://doi.org/10.1016/J.BUSHOR.2019.01.004.

Shah, R., Ward, P.T., 2007. Defining and developing measures of lean production. J. Oper. Manag. 25 (4), 785–805. https://doi.org/10.1016/J.JOM.2007.01.019.

Sharma, A., 2015. Design study of end effectors. Int. J. Eng. Adv. Technol. 4 (3), 2249–8958.

Smelov, V.G., Kokareva, V.V., Malykhin, A.N., 2014. Lean organization of additive manufacturing of aircraft purpose products. Int. J. Eng. Technol. 6 (5), 2304–2309.

Spear, S., Bowen, H.K., 1999. Decoding the DNA of the Toyota production system. Harv. Bus. Rev. 77 (5), 96–106.

Sugimori, Y., Kusunoki, K., Cho, F., Uchikawa, S., 1977. Toyota production system and kanban system materialization of just-in-time and respect-for-human system. Int. J. Prod. Res. 15 (6), 553–564. https://doi.org/10.1080/00207547708943149.

Teece, D.J., Pisano, G., Shuen, A., 1997. Dynamic capabilities and strategic management. Strat. Manag. J. 18 (7), 509–533. https://doi.org/10.1093/0199248540.003.0013.

Teeratansirikool, L., Siengthai, S., Badir, Y., Charoenngam, C., 2013. Competitive strategies and firm performance: the mediating role of performance measurement. Int. J. Prod. Perform. Manag. 63 (2), 168–184. https://doi.org/10.1108/17410401311295722.

The United Nations, 2015. United nations sustainable development – 17 goals to transform our world. https://www.un.org/sustainabledevelopment/.

Tofail, S.A.M., Koumoulos, E.P., Bandyopadhyay, A., Bose, S., O'Donoghue, L., Charitidis, C., 2018. Additive manufacturing: scientific and technological challenges, market uptake and opportunities. Mater. Today 21 (1), 22–37. https://doi.org/10.1016/J.MATTOD.2017.07.001.

Tonelli, F., Evans, S., Taticchi, P., 2013. Industrial sustainability: challenges, perspectives, actions. Int. J. Bus. Innovat. Res. 7 (2), 143–163. https://doi.org/10.1504/IJBIR.2013.052576.

Trappey, A.J.C., Trappey, C.V., Govindarajan, U.H., Sun, J.J., Chuang, A.C., 2016. A review of technology standards and patent portfolios for enabling cyber-physical systems in advanced manufacturing. IEEE Access 4, 7356–7382. https://doi.org/10.1109/ACCESS.2016.2619360.

US EPA, 2020. Sustainable Manufacturing. United States Environmental Protection Agency.

Wiberg, A., Persson, J., Ölvander, J., 2019. Design for additive manufacturing – a review of available design methods and software. In: Rapid Prototyping Journal, vol. 25. Emerald Group Publishing Ltd, pp. 1080–1094. https://doi.org/10.1108/RPJ-10-2018-0262. Issue 6.

Wits, W.W., García, J.R.R., Becker, J.M.J., 2016. How additive manufacturing enables more sustainable end-user maintenance, repair and overhaul (MRO) strategies. Procedia CIRP 40, 693–698. https://doi.org/10.1016/j.procir.2016.01.156.

Womack, J.P., Jones, D.T., 1997. Lean thinking—banish waste and create wealth in your corporation. J. Oper. Res. Soc. 48 (11), 1148. https://doi.org/10.1038/sj.jors.2600967, 1148.

Womack, James P., Jones, D.T., Roos, D., 1990. The Machine that Changed the World. Free Press.

Zott, C., Amit, R., 2010. Business Model Design. : Activity Syst. Perspect. 43, 216–226. https://doi.org/10.1016/j.lrp.2009.07.004.