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The impacts of additive manufacturing technology on lean manufacturing

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ABSTRACT

Purpose: This paper aims to investigate how the use of 3D printing can facilitate the achievement of lean manufacturing objectives. The main goal of the study is to identify the similarities between the two concepts and evaluate how well they complement each other in terms of improving quality, productivity and reducing costs by eliminating waste.

Design/methodology/approach: During this study, the methodology involved conducting a thorough and comprehensive examination of existing literature on lean manufacturing and additive manufacturing. The aim was to provide an overview of the relationship between these two concepts and gain insights into areas that require further research.

Findings: Results obtained indicate a need for more comprehensive and detailed examination of the relationship between lean manufacturing and additive manufacturing in the existing literature. The study highlights the potential synergy between 3D printing and lean manufacturing, suggesting that their integration can enhance quality, productivity, and cost reduction through waste elimination. However, it is important to note that further empirical research is required to validate these findings and quantify the actual impact of combining these two concepts.

Research limitations/implications: This study's limitation is that it relies exclusively on a literature review and does not include any experimental testing to verify the suggested connection between lean manufacturing and additive manufacturing.

Practical implications: This study can help companies understand how the use of 3D printing can aid in achieving lean manufacturing objectives. Additionally, the study can provide insights into best practices for combining lean manufacturing and additive manufacturing and can help companies to optimise the benefits of both.

Originality/value: The conducted literature review provides valuable insights into the relationship between 3D printing and lean manufacturing. This research contributes to the existing body of knowledge by synthesising and analysing previous studies, highlighting how 3D printing can potentially contribute to the achievement of lean manufacturing goals and how those two concepts can complement each other.

Keywords: Additive manufacturing, Lean manufacturing, Lean objectives, 3D printing, Waste

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INDUSTRIAL MANAGEMENT AND ORGANISATION

1. Introduction

Nowadays, 3D printing or additive manufacturing (AM) is receiving considerable attention from both the academic and industrial communities [1]. AM is a material assembly process that makes objects from the data in a 3D model, typically layer by layer, as opposed to subtractive manufacturing methods [2]. It is also known as additive layer manufacturing, 3D printing, digital manufacturing, rapid prototyping, and rapid manufacturing [3]. Additive manufacturing has become an increasingly common technology for creating prototypes, complex parts and custom products. It offers many advantages, such as flexibility, rapidity and the ability to create complex shapes at a lower cost. AM applications are growing in a wide variety of markets, including aerospace, automotive and medical [4].

Lean manufacturing (LM) is a management philosophy based on the Toyota Production System. It aims to improve the company's overall performance by applying a range of tools, techniques and methods [5,6]. It is based on eliminating waste and inefficiencies in the production process by focusing on simplification, standardisation and continuous improvement [7]. One of the primary goals of LM is to eliminate waste of time, money and other resources.

Lean and additive manufacturing share a common feature of both being used to improve production efficiency and quality. However, the relationship between 3D printing and lean manufacturing is rarely studied. The paper will highlight the correlation between lean manufacturing and additive manufacturing. We will also explain how additive manufacturing could be a great way to achieve an effective lean manufacturing system. We will also address the question: What can additive manufacturing contribute to lean manufacturing? To meet this objective, we use a methodology based on analysing some works that study the two concepts.

2. Methodology

This paper's methodology relies on a three-step approach (Fig. 1). The first step consists of highlighting the importance of AM in general as an Industry 4.0 technology, underlining its importance in the global market, and particularly highlighting its emergence in Morocco. The second step aims at reviewing the literature on the relationship between AM and lean manufacturing and outlining the lack of literature on this relation. Finally, the last step is to highlight and discuss the commonalities between the two concepts as tools to increase efficiency and eliminate waste and sources of inefficiency. Figure 1 visualises our research process.

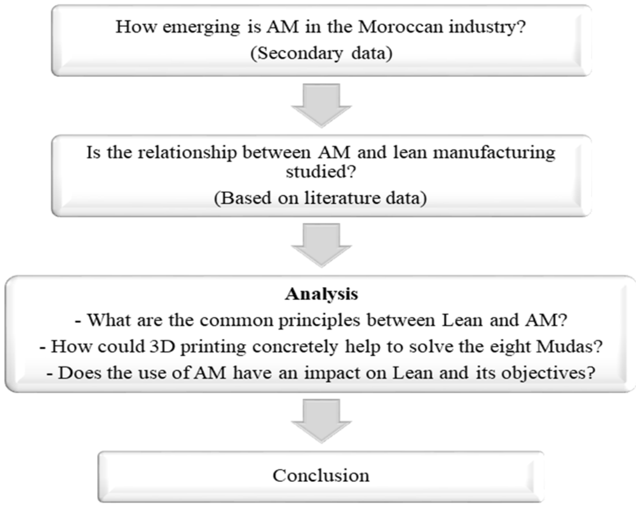

Fig. 1. Research methodology

3. General overview

Producing functional parts involves various manufacturing processes, each with specific capabilities. Subtractive manufacturing removes material for shaping while forming processes reshape without significant removal. Additive manufacturing stands out as an innovative approach involving adding materials to create parts from digital data. According to the ISO/ASTM 52900:2021 standard, it is defined as the process of adding materials to make parts from 3D model data, typically layer by layer, distinguishing it from subtractive and shaping manufacturing methods [8].

AM processes can handle both plastic and metal components, each with its specific technologies and considerations [9]. Plastic AM includes Fused Deposition Modeling (FDM)/Fused Filament Fabrication (FFF) for cost-effective prototyping, Stereolithography (SLA) for high-resolution prints, and Selective Laser Sintering (SLS) for complex geometries. Metal AM employs Powder Bed Fusion (PBF), including Selective Laser Melting (SLM) and Electron Beam Melting (EBM), for strong and intricate metal parts. Directed Energy Deposition (DED) repairs and builds large-scale metal components, while Binder Jetting (BJ) offers high-speed production of small to medium-sized metal parts. Challenges include material selection, post-processing, accuracy, and surface finish. AM enables design freedom, waste reduction, and complexity, but industry-specific factors must be considered. Ongoing advancements address limitations and cater to specific industry needs.

Additive manufacturing has a long history that began in the 1980s when it was developed [10,11]; the period is marked by the birth of stereolithography (SLA). In the 1990s and 2000s, AM applications were only related to model-making and technology prototypes [12]. In recent years, the use of additive manufacturing has grown to print high-precision custom components made from thermoplastic materials [13], as well as to produce functional parts that meet the expectations of customer specifications such as producing spare parts on demand, creating customised mask protectors to combat the COVID-19 pandemic, and making custom medical implants for patients. Besides, many sectors, such as education, research and industry, use additive manufacturing [14].

Indeed, AM is a new technology in full development born during the 4th industrial revolution, Industry 4.0. Figure 2 concisely overviews the four industrial revolutions and their distinctive features.

3D printing continues to play a pivotal role in prototyping and small-scale production. Notably, in 2016, a remarkable breakthrough was achieved by mass production of 3D-printed engine parts [15]. This milestone served as a testament to the increasing interest in utilising 3D printing for large-scale manufacturing, particularly within the aerospace and automotive sectors [16]. The successful production of these engine parts marked a significant turning point, showcasing the technology's immense potential for mass-production applications.

By leveraging 3D printing, companies can achieve significant cost savings of up to 25 per cent and time savings of up to 40 per cent compared to traditional manufacturing methods [17]. The technology not only facilitates the production of complex structures but also ensures their stability and lightweight nature. In recent years, advanced additive manufacturing (AM) techniques have witnessed remarkable growth, expanding their industrial applications to encompass product development, finished goods production, and even mass production. According to a report from Mordor Intelligence, the global market for additive manufacturing is projected to reach $41.5 billion by 2025, exhibiting substantial growth from $10.5 billion in 2015. With a compound annual growth rate (CAGR) of 29.48% over the forecast period (2021-2026), it is estimated to reach USD 63.46 billion by 2026 [18].

Furthermore, 3D printers are increasingly available and can be used by businesses of all sizes as well as individuals. According to a study by the International Energy Agency (IEA), the cost of 3D printers has dropped by 80 per cent since 2010, contributing to their rapid spread. In fact, 2.1 million units of 3D printers were shopped worldwide in 2020; the number is expected to attain 15.3 million units by 2028. Aerospace, automotive, orthodontics, tooling and production systems are the most sectors using 3D printing not only for models and prototypes but increasingly for industrial-scale production [17].

Severalcompanies and start-ups specialising in additive manufacturing have already adopted AM technology in Morocco. These companies offer a range of services, including prototyping, small and large series production, and custom product design. They are actively contributing to the democratisation of additive manufacturing in the country. Furthermore, a French electronics group with expertise in aeronautics has established an industrial skills centre in Casablanca, Morocco, specifically focused on metal additive manufacturing, also known as "3D printing."

Additionally, in Fez, a Moroccan university has developed one of the largest AM platforms in the country and possibly in Africa, boasting approximately 50 3D printing machines. The Moroccan industry has been utilising additive manufacturing for several years, and higher

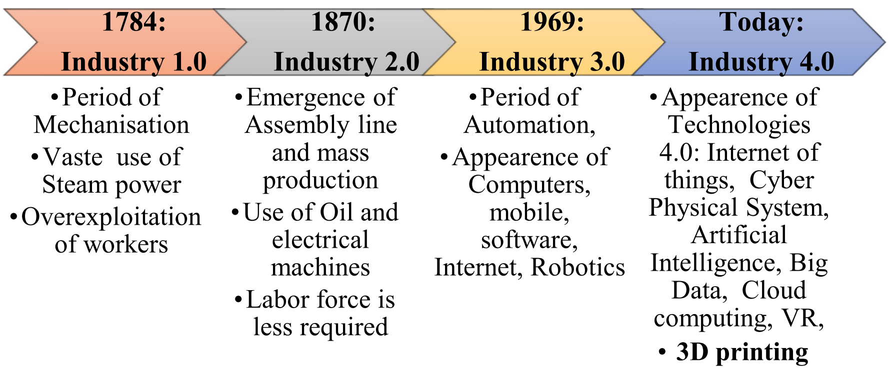

Fig. 2. Characteristics of the industrial revolutions from Industry 4.0 [Own elaboration]

education institutions are also actively participating by establishing a network of university Fab Labs (Fabrication Laboratory) [19]. Moreover, additive manufacturing research and development has significantly improved in Morocco, with the country housing dedicated centres for advancing 3D printing technology [20]. AM can have a positive impact on the economy of Morocco. Its potential benefits include stimulating innovation, reducing production costs, creating jobs, developing new industries, and reducing dependence on imports. AM would enable Moroccan businesses to adopt advanced technologies, locally produce complex parts, and create new employment opportunities. However, the impact will depend on factors such as adoption by businesses, government support, and integration of AM into the country's industrial policies.

AM is experiencing notable progress in the Moroccan market, and its applications are expanding across various sectors:

1. **Healthcare:** In the healthcare sector, additive manufacturing enables the production of customized medical devices and prosthetics using a wide range of biocompatible materials. Advanced 3D printers and scanning technologies are employed to create precise patient-specific models and implants, enhancing treatment outcomes and patient comfort.
2. **Aerospace:** Additive manufacturing is revolutionising the aerospace industry in Morocco, where lightweight and high-performance components are critical. Here, additive manufacturing techniques such as selective laser melting (SLM) and electron beam melting (EBM) are utilised with aerospace-grade materials like titanium alloys and advanced composites. This allows for producing complex geometries and optimised designs, resulting in lighter aircraft parts and improved fuel efficiency.
3. **Automotive:** The automotive sector in Morocco harnesses AM to produce custom parts with high strength and design flexibility. Various additive manufacturing technologies, such as fused deposition modelling (FDM) and stereolithography (SLA), are employed with a wide range of automotive-grade materials like ABS, polyamide, and carbon fibre composites. This enables the creation of engine components, interior accessories, and even complex exterior body parts.
4. **Construction:** Additive manufacturing is also finding its way into the construction industry in Morocco. Large-scale 3D printers are utilised to fabricate construction components using cementitious materials, such as concrete or mortar. By adopting additive manufacturing techniques specific to each sector, Morocco is witnessing advancements in material selection, device capabilities, and process optimisation. Those developments pave the way for enhanced productivity, cost-effectiveness, and design possibilities across industries, positioning additive manufacturing as a driving force behind Morocco's industrial growth.

Additive manufacturing is gaining popularity not only in the manufacturing industry but also in the consumer market, as it offers a new world of opportunities, starting with the absence of geometric constraints and the reduction of waste due to material removal, typical of subtractive manufacturing. In addition, it is a great way to reinforce lean manufacturing objectives [21]. Lean manufacturing (LM) was initially developed within the Toyota Production System in Japan in the 1950s [22]. However, the term "lean manufacturing" was not coined until 1988 by John Krafcik in the article "Triumph of the lean production system" in the MIT Sloan Management Review. Lean production is a holistic system that includes a set of rules, guidelines, tools and techniques to eliminate significant waste in all company processes for continuous improvement [23].

The use of 3D printing could clearly contribute to setting up a Lean Manufacturing model. Although LM and AM are two complementary concepts, authors rarely mention this relation. Ghobadian et al., in their paper, looked at how AM can significantly reduce/eliminate waste [24]. Torres et al., in their work, offer a theoretical and managerial perspective on how AM technology can support green and lean supply chain practices, thereby contributing to better supply chain performance [25]. Sini et al. attempted to study further the defects that affect 3D printed products and propose new ways to control them [21].

While the adoption and industrial use of additive manufacturing is discussed nowadays, we notice that there is little research that relates lean manufacturing and additive manufacturing, so it is necessary to address the question of the level of overlap and complementarity between AM and LM. The answer to this question is of significant importance to the future practice of LM; it is also important to know to what extent AM offers a technological solution capable of eliminating process waste, which is the core of the LM concept.

4. Results and discussion

4.1. Contributions of 3D printing on lean manufacturing

AM is transitioning from manufacturing prototypes in the design phase to industrial use [2]. The transition requires anticipating many questions and, in particular, studying the expected benefits of AM and its effects on the company's performance. One of the questions is the impact of AM's emergence on lean manufacturing objectives.

According to [26], additive manufacturing is an emerging tool that contributes to the sustainable manufacturing of components in several fields, based on the concept of "zero waste"; which is one of the main objective of lean manufacturing. In addition, AM technology improves supply chain efficiency by contributing to waste reduction, elimination of many assembly steps, and reduction of energy consumption, resulting in "leaner" and "greener" production processes [21]. Indeed, one of the benefits of additive manufacturing is to simplify the assembly process. Some parts that had to be made from the assembly of several components are now obtained directly by additive manufacturing in a single part. This can reduce manufacturing time and simplify the components' production [7].

The layer-by-layer production methodology offers other advantages, such as geometry flexibility, as any geometry can be produced in a single operation without additional cost or time constraints. It also reduces resource consumption since only the precise amount of material is needed to create the final product, avoiding the usual waste of traditional manufacturing [3].

A key advantage of 3D printing that complies with the LM objectives is the production of small batches. With 3D printing, a product can be manufactured on demand, eliminating the requirement to stock the product and ensuring easier inventory and information system management, thus satisfying the pulled system and zero stock concepts of lean manufacturing.

One-piece flow is a lean manufacturing principle that involves producing single units or small batches of products simultaneously to reduce waste, improve quality, and minimise lead times [27,28]. AM can enable one-piece flow by producing highly customised parts and products quickly and cost-effectively, often in a single production step [29]. This eliminates the need for large inventories or intermediate storage, minimising wait times and enabling a more efficient and cost-effective production process. AM can also be a valuable tool for enabling one-piece flow in cases where traditional manufacturing methods are not feasible. Overall, AM can help manufacturers optimise their production processes, reduce costs, and improve efficiency by enabling a one-piece flow process in lean manufacturing.

Reducing the cost of inventory obsolescence is an upside to AM deployment. Rather than searching for multiple components in an inventory, the part can be found in an online library and 3D printed. This eliminates the need for large storage space to respond to customer needs quickly [2].

3D printer operations are mostly automated. This property allows separating human work from the machine, which is one of the key aspects of the "Jidoka principle" of lean manufacturing. It is, a key source of quality, productivity and cost reduction. Human-machine separation changes the worker's task from operating the machine to engaging in the process of continuous improvement. In addition, a 3D printer is easy to self-maintain, facilitating the implementation of 5S actions.

Manufacturing facilities equipped with 3D printers can be isolated from other facilities, facilitating an optimal layout that helps eliminate waste, increase flexibility and spread the workload across all 3D printers, which is also in accordance with the Lean manufacturing objectives.

Just-in-time (JIT) manufacturing is a production method in which products are created to meet demand, not in excess or in advance of need. JIT manufacturing is a key Lean manufacturing objective. In the case of additive manufacturing, this objective is confirmed because it is possible to use a 3D printer to manufacture a 3D object on a just-in-time basis, taking into account the necessary printing and shipping times, the location of the customer and the order deadline.

Value Stream Mapping (VSM) is a lean tool used to visually map the value streams of a process, identifying value-added activities and waste. AM can be used in conjunction with VSM to improve processes [30]. It can facilitate value VSM by providing rapid prototyping capabilities. It allows manufacturers to visualise and analyse the flow of materials and information, identify bottlenecks, and optimise the production process. This integration enhances the effectiveness of VSM in identifying and eliminating waste. Moreover, AM enables the production of complex and customised designs with fewer process steps, reducing the potential for defects or errors. This aligns with Lean tools such as error-proofing (Poka-Yoke) and Total Productive Maintenance (TPM) to ensure high-quality output and minimise defects.

Thanks to AM, it is possible to save up to 90% on storage and inventory and transportation costs. Consequently, total production costs can be reduced, and product availability can be improved [2]. Figure 3 shows how 3D printing helps achieve lean manufacturing objectives. It visually represents the relationship between additive manufacturing and lean manufacturing objectives. It is based on a literature review that compiled a list of potential benefits of additive manufacturing for lean manufacturing objectives, categorised into sub-groups.

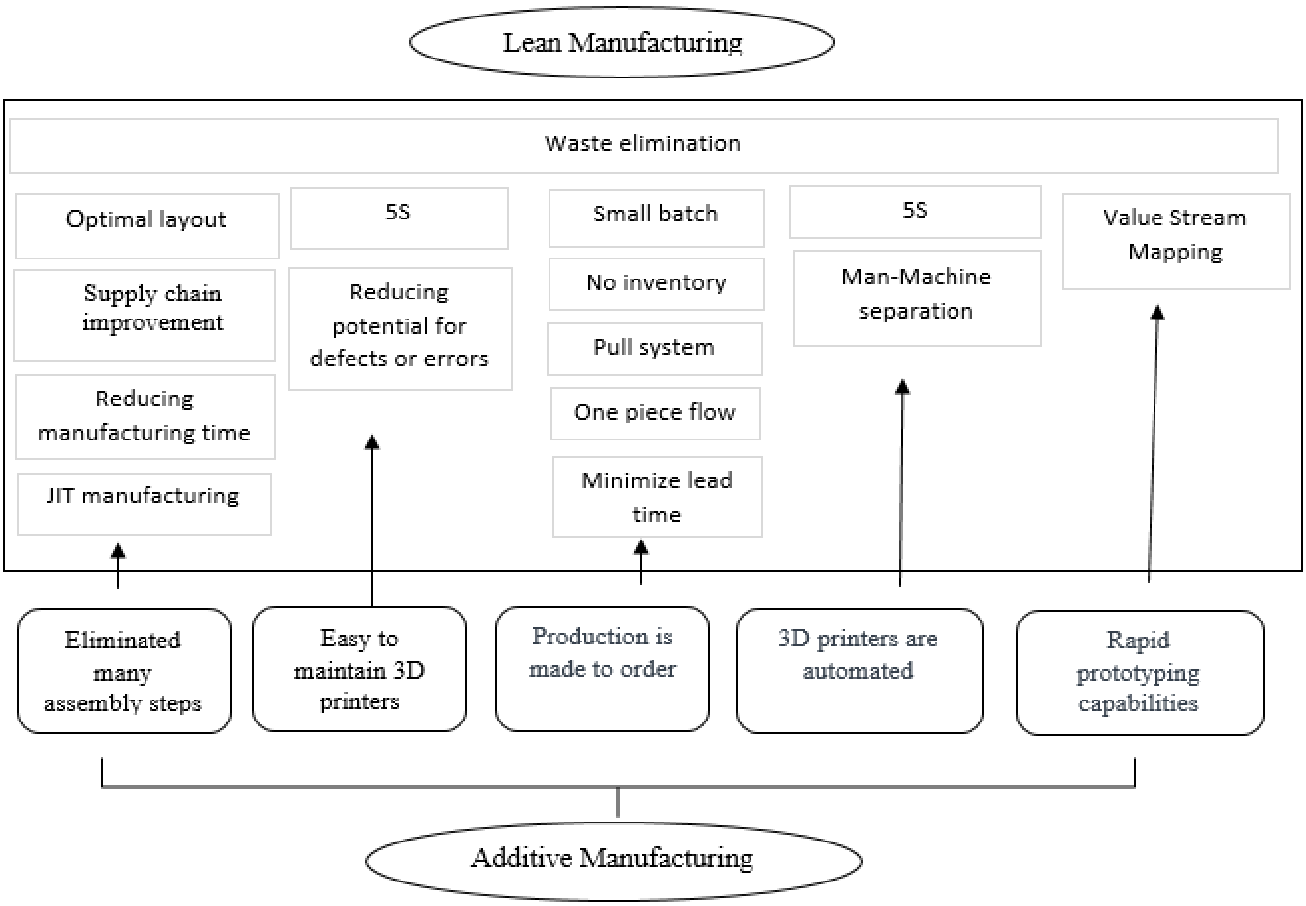

Fig. 3. Contribution of AM in achieving Lean Manufacturing objectives

4.2. 3D printing facing wastes

The objective of Lean Manufacturing (LM) is to maximise customer value by minimising non-value-adding activities, which are referred to as "muda" (the Japanese term for waste). Muda encompasses eight types of waste that should be avoided to achieve lean manufacturing and improve processes [31]. These forms of waste are shown in Figure 4 and can be divided into the categories shown there.

Those wastes directly affect costs as they involve non-value-added operations that do not improve the company's processes or products. In addition to muda, lean manufacturing also addresses two other types of waste: mura and muri. Mura refers to unevenness or variability in the production process, while muri refers to overburdening or straining the process beyond its capacity. Both mura and muri can contribute to increased waste and decreased efficiency in production.

By identifying and eliminating those wastes, organisations can streamline their processes, reduce costs, and improve overall efficiency and quality.

Additive manufacturing can be more efficient and produce less waste compared to traditional manufacturing methods, which are often based on cutting or shaping materials to create a final product.

However, AM can involve some material waste, particularly when extra layers are added to fill gaps or to add detail to the object. Although there are ways to minimise the type of waste, by using design techniques that avoid excessive material use and by using 3D printers that can recycle unused material,

Another potential source of waste in additive manufacturing is the material used to build the printed object. Depending on the material being used, and some may be left over after the object has been printed. This material may be able to be reused for future prints, but it could also be considered waste if it is not being used efficiently.

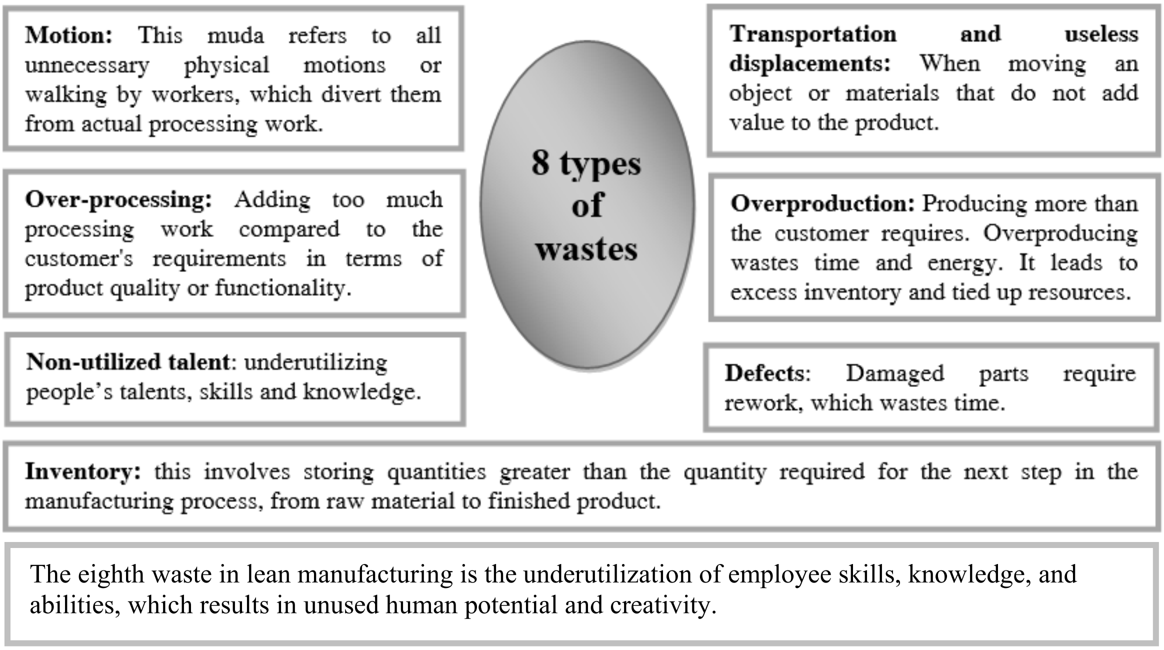

Fig. 4. The eight wastes model of lean manufacturing

It is important to continue to look for ways to minimise any waste and maximise material efficiency when using additive manufacturing. The question then is how 3D printing could help solve the eight Mudas previously mentioned.

- Transportation and useless displacements. Additive manufacturing can help reduce transportation and unnecessary displacements of parts. Since 3D printing produces a part from a digital design without requiring multiple production steps, it eliminates the need to move parts between different manufacturing locations or supply chains, which can significantly reduce transportation costs and lead times.
- Stock management: With traditional manufacturing methods, companies often produce large quantities of products and store them in inventory until they are sold, which ties up capital and increases the risk of excess inventory. By using 3D printing to produce products on demand, companies can reduce the need for a large inventory and minimise waste.
- Motion: When using AM, parts are manufactured entirely within a single workstation (i.e., the 3D printer), which reduces the need for employees to make unnecessary movements during the creation or assembly of parts. This can lead to increased efficiency and reduced labour costs.
- Waiting and lead time: The use of additive manufacturing often entails fewer manufacturing steps compared to traditional methods due to the direct production of parts from a digital design file. As a result, customers may experience shorter lead times and reduced waiting times. Moreover, on-demand production enabled by 3D printing eliminates the need for additional production runs and shipping from different production facilities, allowing products to be delivered immediately after completion.
- Overproduction: Additive manufacturing allows for on-demand production, meaning that products are produced only when needed, reducing overproduction risk. Additionally, 3D printing enables the production of complex geometries that are not easily achievable with traditional manufacturing methods, which can further reduce material waste and the need for excess production.
- Over-processing: Additive manufacturing typically involves fewer processing steps than traditional manufacturing methods, which can reduce the risk of over-processing. With 3D printing, the part is built layer-by-layer using a digital design file and a 3D printing material, and finishing processes are only necessary if required for specific part characteristics or surface finishes.
- Defects: While additive manufacturing can reduce waste in certain areas of the manufacturing process, defects can still occur during the printing process or as a result of other factors such as design flaws or material properties.

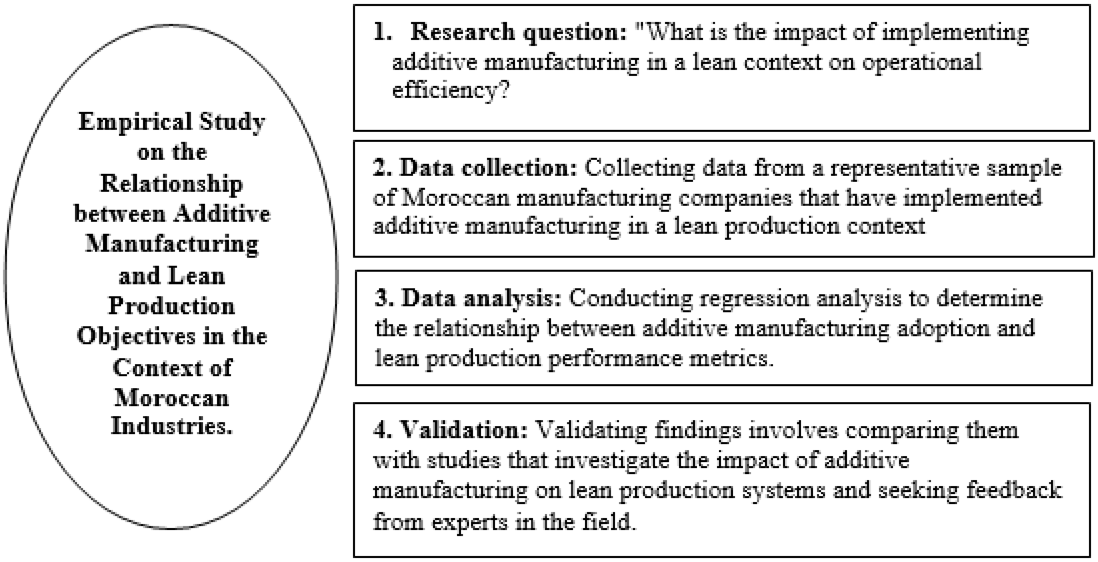

Fig. 5. Design of empirical etudy on the relationship between additive manufacturing and lean production in Moroccan industries

Therefore, quality control measures such as inspection and testing are important to identify and address defects before the final product is delivered to the customer [3].

- Unused human potential or unused creativity. This waste can be addressed through practices such as employee training and involvement, encouraging suggestions and feedback from employees, and creating a culture of continuous improvement. While additive manufacturing may not directly address this waste, it can contribute to a more efficient and streamlined manufacturing process, which can in turn free up time and resources for employees to focus on areas where their skills and knowledge can be better utilised.

For muri and mura waste, additive manufacturing can help to reduce muri of waste by streamlining the production process, simplifying designs, and reducing the need for complex machinery and tooling. Additive manufacturing can help to reduce mura by providing greater flexibility in production, allowing for on-demand production of customised parts and reducing the need for inventory. Itcan help ensure that production is more evenly distributed and that production is more evenly distributed and resources are used more efficiently. Overall, integrate additive manufacturing into lean manufacturing principles can help reduce all types of waste, including muda, muri, and mura, leading to greater efficiency, cost savings, and improved customer value.

Additive manufacturing promises to revolutionise the manufacturing industry by drastically reducing waste and promoting sustainability [24]. AM effectively contributes to waste reduction, a crucial aspect of lean manufacturing. 3D printing lowers costs, minimises material waste, eliminates the need for inventory and produces items based on customer orders. Ultimately, this manufacturing process enhances product quality and reduces lead times.

5. Conclusions and recommandations

Additive manufacturing is a relevant solution for component manufacturing thanks to its numerous advantages, such as free design, simplified assembly, and creation of complex and customised objects with a high degree of accuracy and without the need for expensive tooling. It also allows increasing flexibility and better control of the production chain.

In the work, we have highlighted the importance of this technology and given an overview of its beginnings in Morocco; it has been introduced through associations, start-ups and educational institutions. A key question is how additive manufacturing can promote lean manufacturing and achieve its objectives.

The work allowed us to conclude that 3D printing can reduce material waste, avoid inventory and create only what the customer has ordered. Indeed, a 3D printer can print a

3D object in just-in-time (JIT) by ensuring the shipment of goods when needed, thereby reducing inventory levels and associated costs. Just-in-time manufacturing is a key objective of lean manufacturing. In addition, the operations of a 3D printer are largely automated. The property allows for human-machine separation, a key principle of lean manufacturing. In addition, the most direct advantage of 3D printing is the small batch size, which is also a goal of lean manufacturing.

The relationship between lean manufacturing and additive manufacturing has been a topic of interest in recent years. There are many discussions about the effectiveness of AM as a technology contributing to the principles of sustainability, energy efficiency, and lean manufacturing in its broadest context.

Furthermore, the study is particularly timely given the growing industrial adoption of AM for commercial and localised purposes, which could have significant implications for the Moroccan economy.

The work provides a theoretical foundation that can be used to compare empirical studies and offers valuable insights for researchers, policymakers, and industry practitioners seeking to leverage the benefits of additive manufacturing in promoting lean manufacturing and achieving its objectives.

As a recommendation for future work, conducting an empirical study on the relationship between lean manufacturing and additive manufacturing could yield significant insights into these two production methods as interdependent systems. The study should involve surveying a representative sample of manufacturing companies implementing additive manufacturing in a lean context.

Figure 5 visually captures the core elements of the study, presenting a concise overview of its design and methodology.

Collecting data from the selected sample of manufacturing companies, the study aims to understand the relationship between lean manufacturing and additive manufacturing comprehensively. Careful analysis and validation against existing studies will contribute to deriving valuable insights.

The study's findings can be used to develop a diagram representing the relationship between additive manufacturing and lean production objectives.

Additional information

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