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IDENTIFICATION OF LEAN WASTE IN CONSTRUCTION 3D PRINTING PROCESSES

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ABSTRACT

Recent years witnessed an increase in the use of Additive Manufacturing, or 3D printing, in the construction industry. This is attributed to the promising results that 3D printing can present to the industry including, but not limited to, building customized and complex architectural shapes, integrating more ecological materials and improving sustainable performance in construction projects, and improving productivity and safety in these projects. To maximise its benefits and reach its full potential, 3D printing processes have to be investigated, analysed, and continuously improved.

Lean theory has presented ways to improve the management of operations and processes in manufacturing, construction and other areas. It enables collaboration and reduction of waste, waste minimisation and a lean approach to construction. It is essential to the process of optimising and transforming the construction sector.

The current study aims to examine how lean theory can improve construction 3D printing processes. This is by identifying the lean wastes that may affect the production system during the implementation of construction 3D printing processes. For this purpose, a review of the literature related to 3D printing and lean implementation is conducted. As a result, a list of expected wastes in 3D printing processes is suggested.

KEYWORDS:

Additive Manufacturing, 3D printing, construction, lean, waste.

INTRODUCTION

Construction needs are immense. Cities are having difficulty of renewing their buildings, even though their uses have changed considerably and the need for energy, environmental and health performance, as well as comfort, is stronger than ever. However, faced with this considerable demand, production has never been so difficult. Studies on the weakness of productivity gains in the construction sector are old and yet they remain relevant. Construction is widely criticised for its lack of productivity, poor safety conditions, poor quality, delays and poor environmental performance. In addition, the pace of technical progress in construction is low. The last invention to really impact the construction sector was in 1949 with the invention of the first mobile tower crane by Hans Liebherr.

The changes needed in this industry should be in practices, management methods and ways of thinking. (Albalkhy and Sweis, 2019). There is no one innovative mode of construction in opposition to another deemed obsolete. Nor is there a foreign model to copy. On the other hand, there are very significant upheavals, particularly in the geographical location of added value, jobs and players, which may arise from the generalisation of these practices. Although the French construction industry has shown its capacity to modernise, the challenge ahead is considerable. This challenge is to know how to combine tradition with modernity, to change the approach to construction so as to make it more fluid and flawless, and to introduce the sobriety essential to the renewal of materials and the elimination of waste.

This article therefore proposes to analyse the potential link between a new technology for construction represented by 3D printing and the deployment of lean theory adapted to construction. The question is whether it is possible to recycle waste and reduce waste through 3D printing and the lean method.

The 3D printing and additive manufacturing are used interchangeably to refer to the "process of assembling materials to fabricate objects from 3D model data, usually layer by layer, as opposed to subtractive manufacturing methodologies. (ASTM, 2009). The term first appeared in the writings of Japanese researcher Hideo Kodama in the 1970s and the first commercial 3D printing machine was developed by Charles Hull who patented the stereolithographic manufacturing system. Since then, 3D printing has evolved from the production of small prototypes to the mass production of manufactured parts for different purposes and in different fields. (Sini *et al.*, 2020b).

The construction sector witnessed a late and very slow adoption of 3D printing since the first large-scale construction 3D printer was developed in the late 1990s by Pegna (Žujović *et al.*, 2022). The main components of the 3D printing system are the design, materials, and process. The 3D printing process is based on software and hardware integration as shown in Figure 1. The software part is based firstly on the modelling of the object (using software such as AutoCAD, Solid Works, or others), then exporting the model to another software to identify the dimensions of the layers (slicing), and then generate a G-code program file to be read by the printer and print the object. The hardware part is composed of a printer (gantry or robotic) that is connected to a material delivery system; this system includes a mixer, pump, and hose pipe to deliver the materials to the nozzle head to deliver the materials in the shape of additive layers. The hardware part also includes a controller to control the printer and pump according to the design (shape, size, etc.) of the printed object.

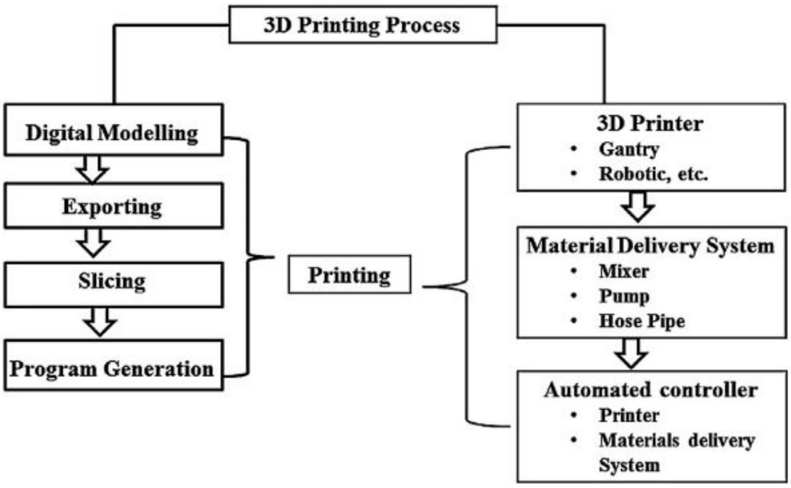

Figure 1. The process of 3D printing for the construction industry (Paul *et al.*, 2018).

The use of 3D printing can bring several benefits to the construction sector. For example, 3D printing offers architecture and designers a great deal of freedom in designing creative and customised forms that are not always possible in conventional buildings. It also saves more than half of the design and construction time, making it very suitable for building quick shelters in case of disaster or war... (Schuldt *et al.*, 2021). In terms of cost, 3D printing normally requires a high investment, but it saves on the costs of material handling, overproduction, human error, formwork and so on.

As a social and health issue, the 3D printer transforms jobs. It is useful because it eliminates the manual formwork stage, regardless of the complexity of the shapes. The 3D printer also needs supervisors who control the work of the machine and supply it with material. Engineers and technicians are also needed who can design the 3D plans to be built and use the software. So new trades have to be created, adapted to both men and women. 3D printing introduces a human and social dimension insofar as it makes it possible to improve working conditions and prevent possible health risks and risks of discomfort (Krimi, Lafhaj and Ducoulombier, 2017; Lafhaj *et al.*, 2019; Olsson *et al.*, 2019; Romdhane, 2020; Schuldt *et al.*, 2021) . THowever, these benefits have to be weighed against the reduction in employment opportunities. (Dixit, 2019; Olsson *et al.*, 2019; Schuldt *et al.*, 2021)

Time issue, 3D printers reduce manufacturing time. Opening up fast and personalised markets, any request for creation, even in small numbers, can be realised in record time without increasing production costs. In a matter of hours or even days, prototypes can be made using this technique, whereas it used to take months. Printing complex shapes will be faster with the 3D printer than with current methods. Depending on the manufacturer's wishes, the printing will be done either in the factory for greater safety, or on site, which would save even more transport and/or installation time.

3D printing also has many benefits for improving environmental performance in the construction sector due to its contribution to reducing greenhouse gas emissions, reducing waste, saving raw materials, reducing transport operations and saving energy. Many researchers have presented the principles (e.g. Lafhaj and Dakhli, 2018) that summarise the benefits of 3D printing based on three main categories as shown in Figure 2; input data, conversion process and output data.

Despite its many advantages, 3D printing has not shown its full potential in the construction sector. Although 3D printing is gaining popularity in the sector, it is still at the research and development level, limited to a small number of teams and applied in small-scale projects (Dixit, 2019; Schuldt *et al.*, 2021). This is due to several challenges faced by this technology in the construction sector, including printability, constructability and open time of materials, scalability, ability to print large buildings, high capital costs, lack of skilled workers, low levels of standardisation and redundancy, and cyber security risks. (Olsson *et al.*, 2019; Romdhane, 2020).

The main reason that has limited the development of this technology is that it has not been accompanied by the change in the building system that surrounds it. The arrival of a new machine must be linked to a strategic reflection on the optimisation of processes. This is what the lean philosophy can bring to the construction sector.

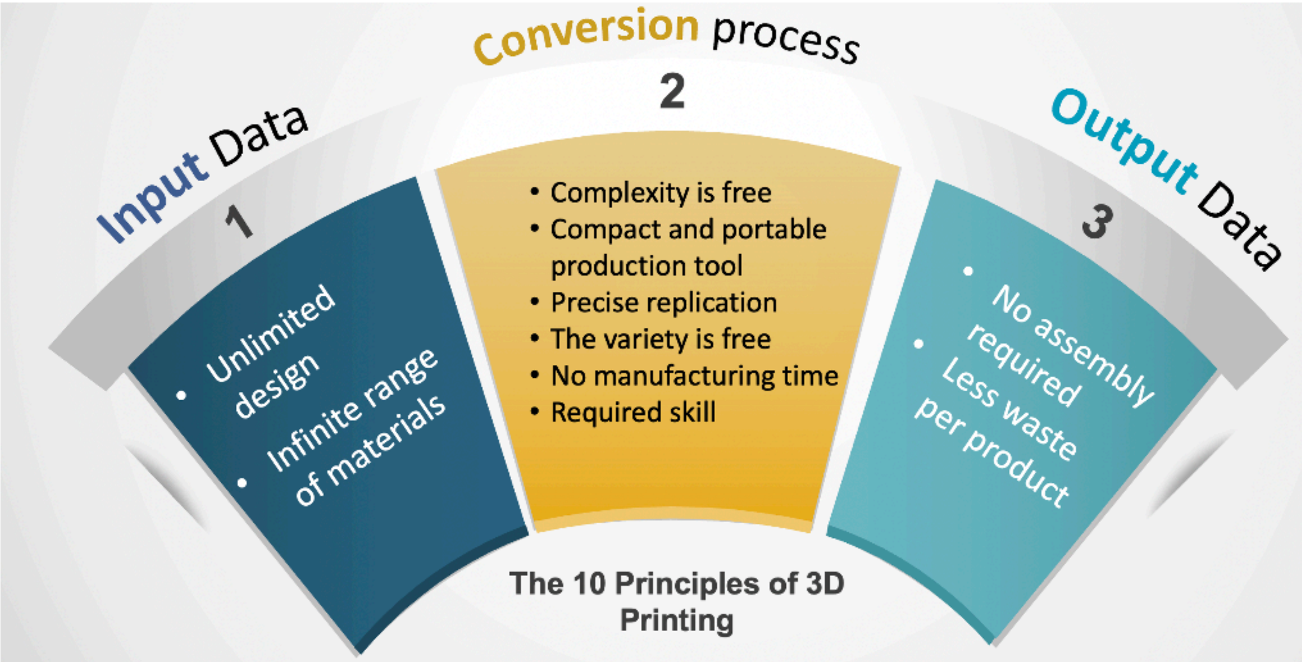

Figure 2. The 10 principles of 3D printing.

Indeed, the philosophy of lean, which has been introduced in the manufacturing sector, can help improve 3D printing processes by identifying and eliminating non-value-added activities (waste) and avoiding allocating resources (time, money, human resources, etc.) to these activities. Rooted in reality, the lean approach starts with the work of the moment while keeping in mind the final delivery of the product and the initial requirement of the desired quality.

In the following sections, we present the synergies between 3D printing and lean thinking, and how the two concepts can be integrated.

SYNERGIES BETWEEN LEAN AND 3D PRINTING IN CONSTRUCTION

The main principles of lean are identifying the value, mapping the value stream, creating flow, establishing pull, and working for continuous improvement (Womack and Jones, 1996). The value that can be provided in the production system is a core concept in lean thinking and it should govern all the practices in the system. Therefore, lean researchers and practitioners stressed that lean implementation should understand how the value streams between the different activities in any system and then improve the activities that add value and eliminate those that do not. Accordingly, lean literature distinguishes between three main types of activities; adding value activities (should be continuously improved and optimized), non-adding value activities or wastes (should be eliminated), and necessary non-value adding activities (wastes that are very difficult to be eliminated but should be improved). The lean wastes are defects, motion, waiting, transportation, excess processing, overproduction, inventory, and non-utilized talents (shown in Table 1).

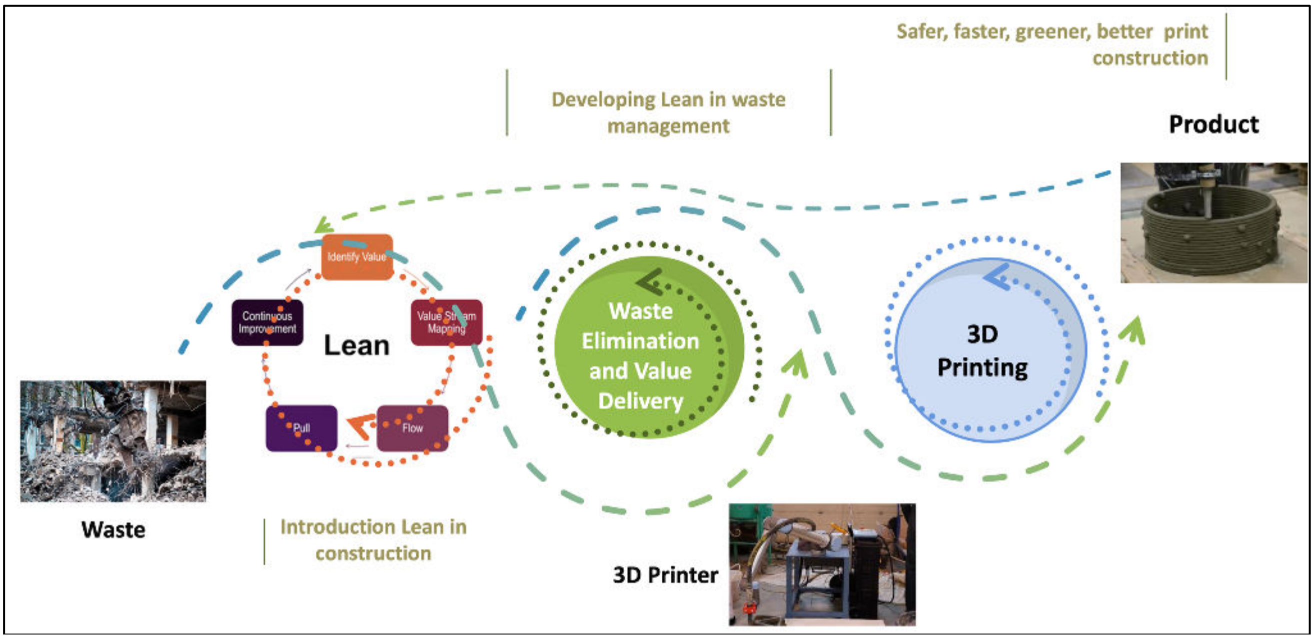

Figure 3. Research Objectives.

The current study uses the concept of the value and the elimination of non-value-adding activities or wastes to study the synergies between lean and 3D printing in construction. This is by understanding how 3D printing can contribute to the achievement of lean principles in construction projects (i.e. delivering value and waste elimination) and how lean in turn can help in improving 3D printing processes by identifying the wastes and eliminating them (as shown in Figure 3).

To achieve this objective, a literature review was conducted, in which the search was using the following keywords: lean AND (wastes OR waste OR "value-adding activities" OR "non-value adding activities") AND ("3D printing" OR "3D print" OR "three-dimensional printing" OR "additive manufacturing" OR "additive construction") AND ("construction" OR "building" OR "buildings" OR "built environment"). The results of the search showed that the main focus in the literature was on how 3D printing can eliminate lean waste, and only a few studies covered the contribution of lean to the improvement of 3D printing processes.

How 3D printing can eliminate lean wastes

Many authors and researchers agree that 3D printing has a significant role in eliminating lean wastes in construction when it is compared to conventional building methods (Rouhana *et al.*, 2014; El sakka and Hamzeh, 2017; Ghobadian *et al.*, 2020; Hamzeh *et al.*, 2021; Khan and Leicht, 2022):

The first reason why 3D printing is "leaner" than the conventional ways of construction is due to the differences in materials management in the two systems. 3D printing requires only a limited amount of materials that are necessary for the printing process and the materials move directly from the mixers to the hosepipe and the printed object. This means that there is no need for unnecessary inventory in form of unnecessary areas for materials storage, work-in-progress, or storage areas for final products. This also helps to decrease the waiting time for materials handling and transportation and achieve Just-in-time (JIT) principles.

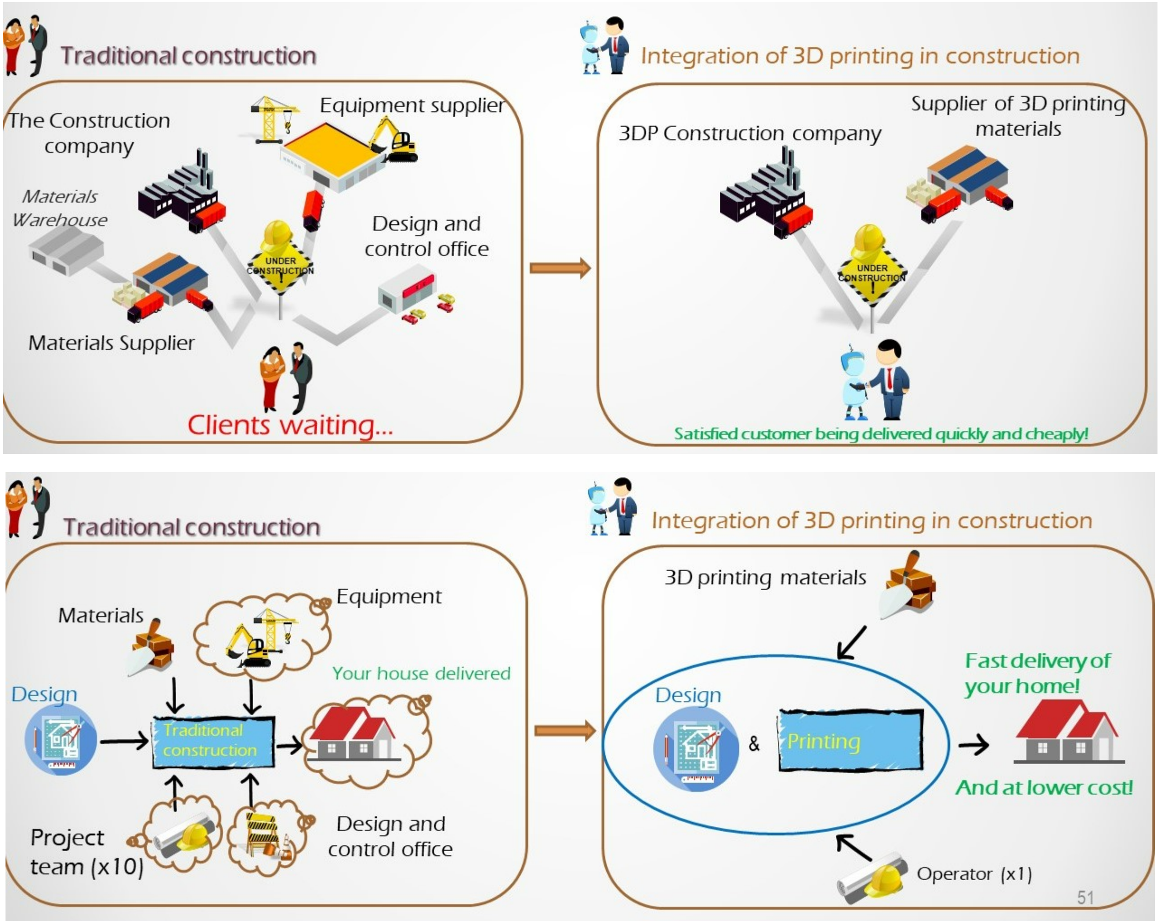

Figure 4. Impact of 3D printing on lean wastes in the construction (Lafhaj and Dakhli, 2018)

Waiting time is also reduced due to the reduction of inactive time needed for curing concrete, formwork time, setup time to produce different types of items, and supply lead time for materials and equipment delivery and transportation, in addition to the reduction of waiting for tools and labours movement and intervention. Figure 4 shows how 3D printing helps to avoid lean wastes in general, and waiting wastes in particular due to the avoidance of logistics problems and simplicity and stability of the production system social ecosystem.

3D printing also offers opportunities for error-proofing applications and the removal of defects. This is due to the possibility of noticing the defects in an easier way than that in conventional construction where defects are invisible due to the forms. The detection of these defects helps to avoid wasted time for repair and rework.

Additionally, as 3D printing is done by one crew and one printer (in most cases), it helps to minimize the movement of labours, machines, materials, and equipment. Consequently, it helps to decrease transportation and motion wastes. Furthermore, due to automated production, 3D printing helps to decrease over-production and excess processing wastes. Figure 5 summarizes some of the factors that help to eliminate waste in the 3D printing systems as found in the reviewed studies.

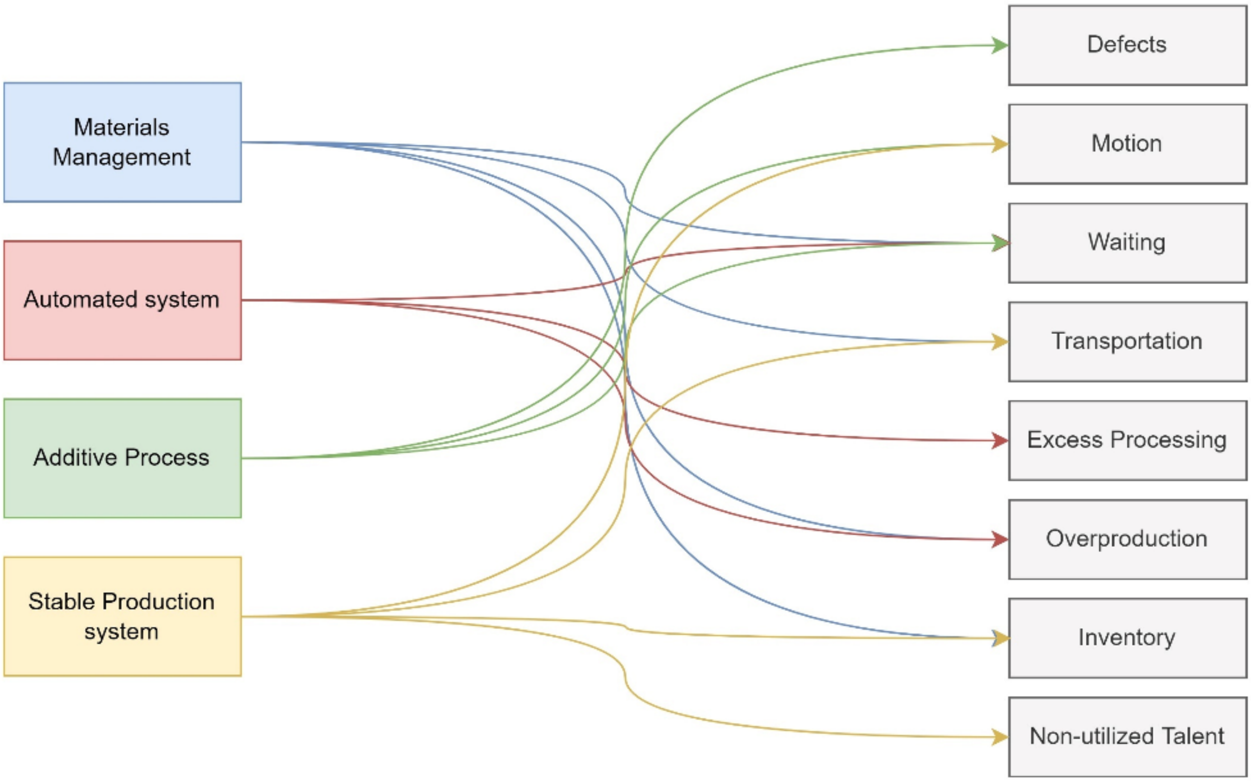

Figure 5. Factors help to reduce wastes in 3D printing processes

Lean wastes in 3D printing processes

Although 3D printing can help in achieving lean principles and delivering higher value to the client, many non-value-adding activities may occur in the 3D printing processes (Groneberg *et al.*, 2021, 2022). The most apparent type of wastes that can happen in 3D printed buildings or building components is defects. According to Sini et al (2020a), 3D printing is still immature to guarantee the quality of the final printed object and is still unable to eliminate the wastes of defects.

Many factors affect the quality of the printed object such as the materials properties, print speed, layer thickness, layer time, print path, nozzle shape, size, and standoff distance (Schuldt *et al.*, 2021). For instance, with regard to print speed, too slow printing would result in reduced bonding between the layers, while too quick printing would prevent the development of the layer's strength that is needed to carry the new layer.

Concerning the materials, despite the great focus on materials in the construction 3D printing literature, there are still no codes or standards for the tests needed for 3D printing materials (Schuldt *et al.*, 2021). The lack of these codes raises some questions regarding the wasted materials, number of defects, and even safety of the 3D printed buildings. So far, many characteristics affect the printability of the materials and differ from one place to another; for instance, what can be printable in hot areas may not be printable in very cold locations in the world. This increases also the risks of waiting wastes. Offsite printing might be one of the effective solutions to solve this problem, but it may present some limitations regarding the design and size of the printed object. In offsite printing, defects may also occur during the transportation and installation of the object.

Defects may also appear in the design model due to the lack of proper communication and collaboration (e.g. in the shape of rework) or just like any other design process in the shape of revisions, deviation from customer requirements and need, or damaged, lost, or incomplete files. Defects in the automated printer (robot or gantry) are another serious problem that may face the 3D printing process; especially when there is only one printer that cannot be easily fixed or repaired.

Waiting wastes are one of the most frequent wastes in conventional construction methods. Similarly, waiting in 3D printing can occur for many reasons, and normally it can be connected to defects. For instance, defects that may happen in the printer would result in waiting wastes for maintenance and spare parts. Knowing that 3D printing can be a suitable solution for remote areas and areas affected by unusual events such as wars and disasters (Schuldt *et al.*, 2021), the impact of waiting might be very serious.

Waiting for wastes are also possible due to the additive process due to the need for quality measures and control. As mentioned above, defects during 3D printing are easier to detect than those in the conventional or manual construction methods; however, the occurrence of these defects requires hinders the continuity of the work. Repairs, measurements, and retesting would result in idle machines or crews and delays in the processes. Another example of waiting waste is the idle nozzle due to the concrete solidification in the pipeline (Rouhana *et al.*, 2014).

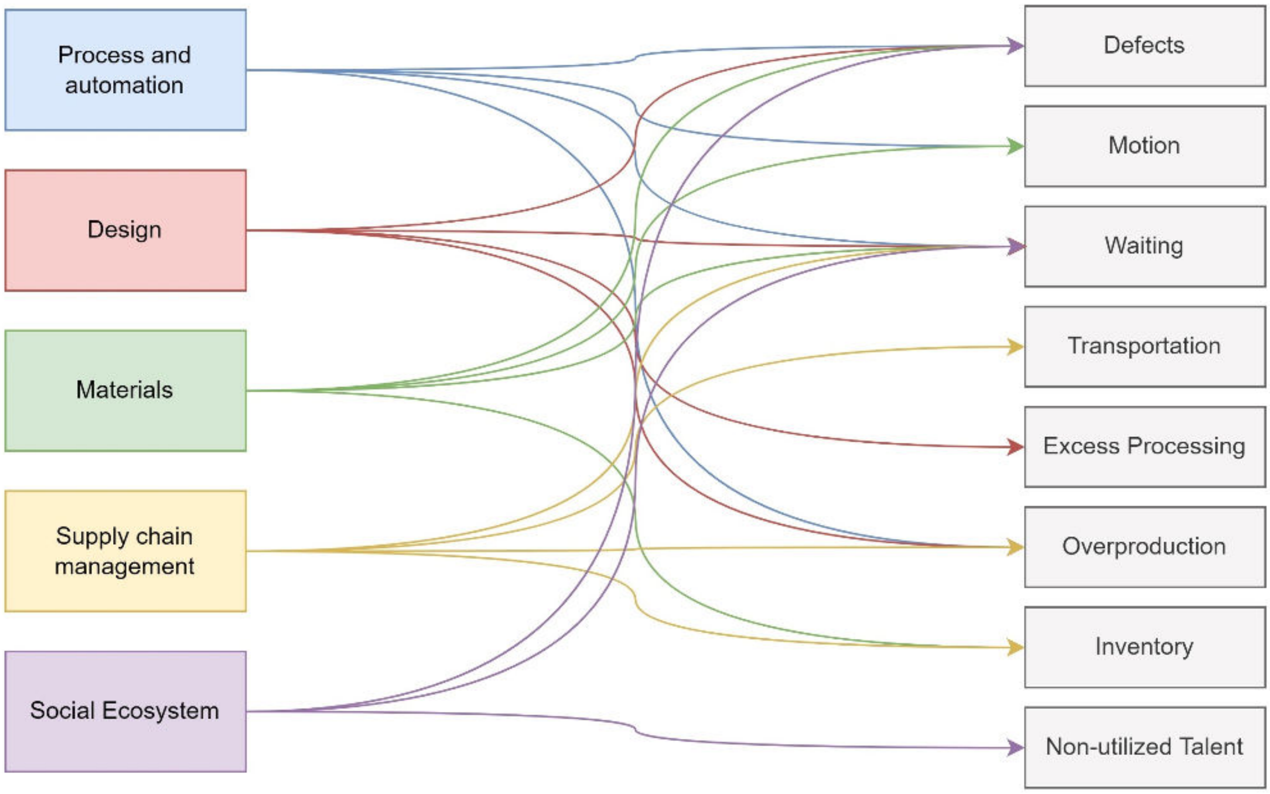

Figure 6. Categories for lean waste sources in the 3D printing processes.

Non-utilized talents can be noticed when there is a lack of expertise in dealing with the 3D printing system. This might result from the lack of standardised printers in the market and the lack of skilled workers. The robots that are currently on the market cannot be modified by the company that purchased them. To meet specific demands, the company must therefore call on another 3D printing company to subcontract or buy a new robot and train its staff to use it. The lack of standardisation and redundancy in the work may also cause more waiting wastes.

Similar to any other production system, other types of wastes may appear in the 3D printing system due to several reasons. For instance, clashes between the different stakeholders can result in delays or defective design; a non-optimal printing path might be the reason for unnecessary motion and defects; and unreliable logistics system in the on-site and off-site printing (for raw materials, components, final product…etc.) can produce inventory, overproduction, transportation, and waiting wastes. Figure 6 shows the categories for lean waste sources in the 3D printing processes, and in Table 1, we show some examples of lean wastes in these processes based on the definition provided by El Jazzar and Nassereddine (2021).

Table 1. Examples of lean wastes in 3D printing processes.

Category	**Definition** (El Jazzar and Nassereddine, 2021)	**Examples in Construction 3D Printing**
Defects	Defective product, unacceptable quality, rework/repair/replacement is needed	Defective layer Defects while objects/parts transportation

		Design error/redesign Unprintable materials Defects in robot
Motion	Unnecessary movement that does not add value	Non-optimal path for printing
Waiting	Delays or wasted time while waiting for a machine, product, labour, action, decision, information…etc.	Waiting for maintenance Waiting for design information/decision Waiting for quality measurement Waiting for wearing personal protective equipment Idle machine/crew (e.g. due to concrete solidification in the pipeline) Meetings with no decisions
Transportation	Movement of materials or equipment that does not add value	Transportation of spare parts Sending components back and forth between different sites More components or workers need to be brought to the site
Excess Processing	Unnecessary steps in the production/ produce something is not valued or required by the client	Post-processing due to the defects
Overproduction	Producing too much or too early/ ordering too much materials	Overdesign Early preparation of mortar Pre-installation Too late/too early printing Too much flow through the printing head
Inventory	Excess storage of materials/WIP/unused tools	Lost files More mortar than needed
Non-Utilized Talents	Non-utilized crew and skills	Lack of skilled workers in the crew

The lean theory has presented several tools to improve performance in construction processes and projects. In dealing with wastes, Hannis Ansah et al (2016) classifies lean construction tools into three main categories:

- Waste detection tools: such as value stream mapping (VSM), construction process analysis, Muda walk, and spaghetti diagram
- Waste processing tools: such as 5 Why, Pareto analysis, and Fishbone diagram (or Ishikawa diagram)
- Waste response tools: such as 5S, Last Planner Systems (LPS), work standardisation, check sheets, Just-in-time, A3 problem solving, visual management (VM), and others.

Companies and practitioners in the construction of 3D printing projects can use these tools to identify and remove the wastes. An example of the use of these tools is the integration between VSM, 5Why, and A3 problem solving; in which a current VSM can be used to map the value stream during the 3D printing processes, then based on the 5 Why and A3 problem solving, actions can be made to develop and apply future VSM to improve the performance in the processes.

Nevertheless, lean is not a set of tools, rather, it is a philosophy that is based on delivering value for the client, respect for people and partners, creating flow, problem-solving and continuous improvement, and collaboration.

Therefore, the implementation of the tools is not enough and the commitment to the principles of lean is what can help to improve 3D printing processes.

CONCLUSION

It is vital that the construction sector succeeds in its transformation towards sobriety and reduces its carbon impact. 3D printing and lean thinking are among the most important concepts that can revolutionise the construction sector and produce more stable and reliable production systems in the sector. Both concepts can benefit from each other to improve the performance of construction projects. 3D printing can help eliminate much of the expected waste when compared to conventional construction methods. Lean construction can affect 3D printing processes by providing opportunities for continuous improvement of these processes. From our point of view, improvements will come in the reduction of additional waste such as waiting times, unnecessary travel, poor quality resulting from execution errors, problems with storage, transport of materials, overproduction, overquality using too much material, mismanagement of skills and loss of creativity and team spirit. The current study raised some examples regarding the integration of these two concepts. Nevertheless, this study is a conceptual study that should be supported by real-case examples from construction projects. Future studies can examine specific cases of 3D printing, which will help to identify more wastes and provide more opportunities to maximize the performance in construction 3D printing projects.

REFERENCES

Albalkhy, W. and Sweis, R. (2019) ‘Assessing lean construction conformance amongst the second-grade Jordanian construction contractors’, *International Journal of Construction Management*, pp. 1–13. doi: 10.1080/15623599.2019.1661571.

ASTM, ‘The American Society for Material and Testing’ (2009) *Standard Terminology for Additive Manufacturing Technologies*. ASTM International, West Consholhocken, US. Available at: https://web.mit.edu/2.810/www/files/readings/AdditiveManufacturingTerminology.pdf.

Dixit, M. K. (2019) ‘3-D Printing in Building Construction: A Literature Review of Opportunities and Challenges of Reducing Life Cycle Energy and Carbon of Buildings’, *IOP Conference Series: Earth and Environmental Science*, 290(1). doi: 10.1088/1755-1315/290/1/012012.

Ghobadian, A. *et al.* (2020) ‘Examining legitimatisation of additive manufacturing in the interplay between innovation, lean manufacturing and sustainability’, *International Journal of Production Economics*, 219(July 2017), pp. 457–468. doi: 10.1016/j.ijpe.2018.06.001.

Groneberg, H. *et al.* (2021) ‘Development of a systematic approach to identify non-value-adding operations in the LBM process chain’, *Procedia CIRP*, 104(January), pp. 1613–1618. doi: 10.1016/j.procir.2021.11.272.

Groneberg, H. *et al.* (2022) ‘Concept for the reduction of non-value-adding operations in Laser Powder Bed Fusion (L-PBF)’, *Procedia CIRP*, 107(2021), pp. 344–349. doi: 10.1016/j.procir.2022.04.056.

Hamzeh, F. *et al.* (2021) ‘Lean Construction 4.0: Exploring the Challenges of Development in the AEC Industry’, in *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC)*. Associate Professor, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada, hamzeh@ualberta.ca, orcid.org/0000-0002-3986-9534, pp. 207–216. doi: 10.24928/2021/0181.

Hannis Ansah, R. *et al.* (2016) ‘Lean Construction Tools’, in *Proceedings of the 2016 International Conference on Industrial Engineering and Operations Management*. Detroit, Michigan, USA, pp. 784–793.

El Jazzar, M. and Nassereddine, H. (2021) ‘Interactions Between Construction 4.0 and Lean Wastes’, *Proceedings of the International Symposium on Automation and Robotics in Construction*, 2021-Novem, pp. 971–978. doi: 10.22260/ISARC2021/0131.

Khan, M. A. H. and Leicht, R. M. (2022) ‘Categorization of Construction Tasks for Robotics Using Lean vs Value-Added Effectiveness Framework’, in *30th Annual Conference of the International Group for Lean Construction (IGLC)*. Edmonton, Canada, pp. 832–843. doi: 10.24928/2022/0195.

Krimi, I., Lafhaj, Z. and Ducoulombier, L. (2017) ‘Prospective study on the integration of additive manufacturing to building industry—Case of a French construction company’, *Additive Manufacturing*, 16, pp. 107–114. doi: 10.1016/J.ADDMA.2017.04.002.

Lafhaj, Z. *et al.* (2019) ‘Experimental Approach for Printability Assessment: Toward a Practical Decision-Making Framework of Printability for Cementitious Materials’, *Buildings*, 9(12), p. 245. doi: 10.3390/BUILDINGS9120245.

Lafhaj, Z. and Dakhli, Z. (2018) ‘State of the art of industry 4.0: Strategy and Vision of France- The digital age driven by 3D printing: Which positioning for the construction of the future?’, in *Global Career Design Seminar*. Kyoto, Japan.

Olsson, N. O. E. *et al.* (2019) ‘3d-printing technology in construction: Results from a survey’, *Emerald Reach Proceedings Series*, 2, pp. 349–356. doi: 10.1108/S2516-285320190000002044.

Paul, S. C. *et al.* (2018) ‘Fresh and hardened properties of 3D printable cementitious materials for building and construction’, *Archives of Civil and Mechanical Engineering*, 18(1), pp. 311–319. doi: 10.1016/j.acme.2017.02.008.

Romdhane, L. (2020) ‘3D Printing in Construction: Benefits and Challenges’, *International Journal of Structural and Civil Engineering Research*, 9(4), pp. 314–317. doi: 10.18178/ijscer.9.4.314-317.

Rouhana, C. M. *et al.* (2014) ‘The reduction of construction duration by implementing contourontour crafting (3D printing)’, in *22nd Annual Conference of the International Group for Lean Construction (IGLC)*. Oslo, Norway, pp. 1031–1042.

El sakka, F. and Hamzeh, F. (2017) ‘3d Concrete Printing in the Service of Lean Construction’, in *25th Annual Conference of the International Group for Lean Construction*. Heraklion, Greece, pp. 781–788. Available at: https://iglcstorage.blob.core.windows.net/papers/iglc-c515170f-bcc7-4912-9401-ad7964246962.pdf.

Schuldt, S. J. *et al.* (2021) ‘A systematic review and analysis of the viability of 3D-printed construction in remote environments’, *Automation in Construction*, 125(February). doi: 10.1016/j.autcon.2021.103642.

Sini, F. *et al.* (2020a) ‘A Lean Quality Control Approach for Additive Manufacturing’, *IFIP Advances in Information and Communication Technology*, 594, pp. 59–69. doi: 10.1007/978-3-030-62807-9_6.

Sini, F. *et al.* (2020b) *Lean management in Additive manufacturing : a methodological proposal for quality control*. Politecnico di Torino. Available at: https://webthesis.biblio.polito.it/14001/1/tesi.pdf.

Womack, J. and Jones, D. (1996) ‘Beyond Toyota: How to root out waste and pursue perfection’, *Harvard Business Review*, 74, pp. 1–16.

Žujović, M. *et al.* (2022) ‘3D Printing Technologies in Architectural Design and Construction: A Systematic Literature Review’, *Buildings*, 12(9), p. 1319. doi: 10.3390/buildings12091319.