The Analysis of Lean Wastes in Construction 3D Printing: A Case Study

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Abstract –

One way to improve the construction sector is by paving the way toward adopting innovative technologies and practices that may contribute to improving efficiency and performance in this sector. During the last few years, lean construction and 3D printing have been considered compatible with this goal. Nevertheless, their integration together is still overlooked. The current study aims to fill this gap by analyzing the non-value-adding activities (waste) in 3D printing operations. To do so, two-phase 3D printing laboratory investigations were conducted and analyzed. The results showed room for efficiency improvements in 3D printing processes when integrated with lean thinking as the proportion of waste was reduced from 24% to 13.1% following the introduction of lean to the 3D printing system. The study offers researchers and practitioners an example of lean adoption in 3D printing operations that can be even adopted in other sectors.

Keywords –

Additive manufacturing, 3D printing, Lean, Lean construction, waste elimination.

1 Introduction

Additive manufacturing (AM), more commonly known as three-dimensional (3D) printing, is an innovative technology that is used to fabricate objects based on successive addition of materials [1]. Without using tools or fixtures, this successive process allows 3D printing to produce numerous on-demand complex structures and geometric shapes that are not easy to produce with other fabrication techniques [2]. This has made 3D printing one of the trendiest innovative technologies in the last few years. In 2021, the global revenue of the 3D printing sector exceeded 10 billion US dollars with expectations of growing to more than 50 billion US dollars in 2030 [3]. This was due to the growing level of maturity the sector is entering and the higher demand for 3D-printed products due to the global logistics challenges that appeared after the COVID-19 pandemic [4-5].

The construction industry can benefit from 3D printing applications to face the challenges it encounters (e.g. poor productivity, delays, poor quality, and poor environmental performance) [6-7]. One example of how 3D printing can be advantageous in architecture and design is its ability to create customized structures that are not always possible with conventional construction methods. 3D printing is capable to fabricate complex structures with more design flexibility and easier ability to cope with design changes even after the pre-planning phase [7]; unlike the traditional construction methods where design changes have a significant impact on the time, cost, and even relationships between stakeholders in the projects [8-10]. Additionally, 3D printing contributes to saving a significant amount of time during the design and construction process, making it an ideal solution for constructing quick shelters in emergencies or wartime conditions [11]. In terms of the cost, despite the large capital needed for the initial investment due to the expensive 3D printing equipment, the overall cost of the projects can be decreased due to the savings in materials management (e.g. handling, delivery, acquiring), labor, framework, and costs resulted from design changes, overproduction, and human errors [6-7]. According to Mohd Tobi [12], the use of 3D printing in housing construction can help by saving up to 35% of the total house price in the UK. In regards to the sustainable impact, 3D printing offers opportunities to reduce the generation of waste, use more eco-friendly materials, and reduce greenhouse gas emissions (GHG) resulting from several sources such as materials production and transportation and machines use [6,13,14]. According to a report by market research company "Markets and Markets", 30-60% of the generated waste during construction can be saved when using concrete 3D printing. Social sustainability factors such as the comfort of workers, safety, and healthy working conditions can also improve due to 3D printing

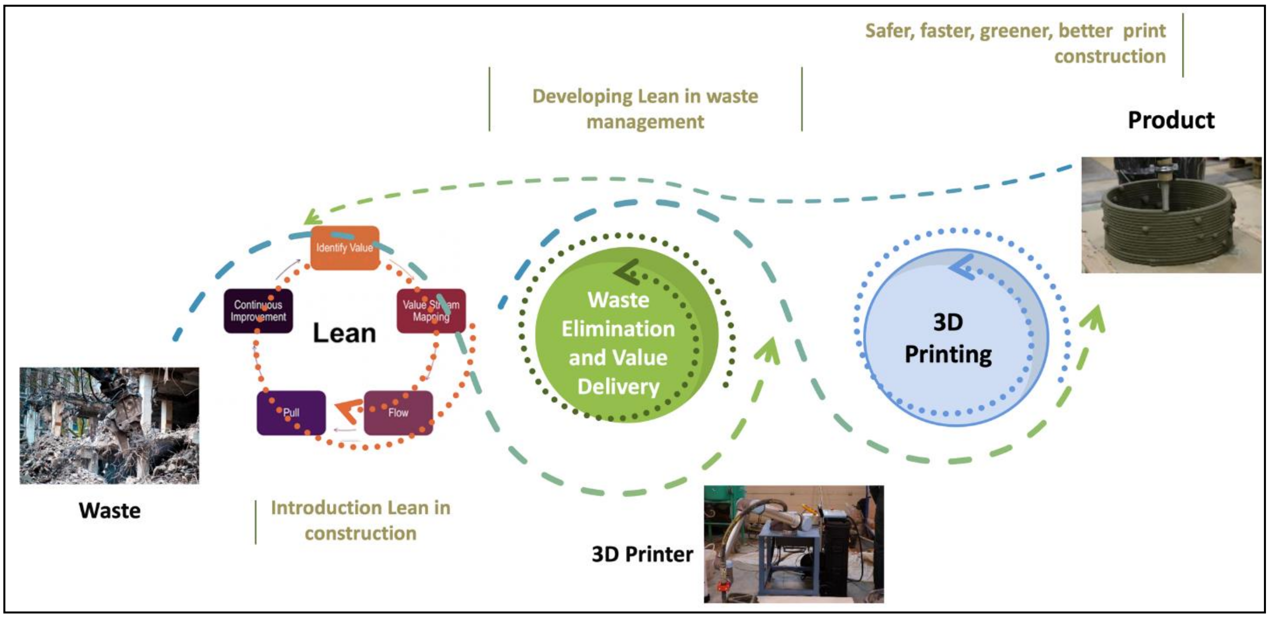

Figure 1. 3D printing and lean integration [6].

[11,13,15,17].

However, despite its many advantages, 3D printing has not yet significantly impacted the construction industry. While it is gaining popularity among professionals in this sector, it remains at an early stage of development and is only used in small-scale projects by a few teams [6,11,14].

According to Lafhaj et al [6], one of the main reasons that this technology has not been implemented at a wider scale is the fact that there has been no corresponding change in the system of building and there has not been enough work to link it with other managerial concepts and process optimization philosophies such as the philosophy of lean. Lean philosophy can help construction companies optimize their processes so that new technologies can be introduced smoothly and effectively. In their study, Lafhaj et al [6] pointed to a two-direction relationship between lean and 3D printing (as shown in Figure 1). Their study also listed a set of lean wastes that 3D printing can eliminate and other wastes that may appear during the 3D printing process. Based on this relationship, the performance in construction can be improved by benefiting from the two concepts. On one side, 3D printing can significantly contribute to eliminating various wastes and generating value for the client; which are core concepts of lean philosophy. On the other side, lean principles can help in improving the production system of construction 3D printing and achieving safer, faster, greener, and better printing.

Despite the existing potential to improve construction production systems through the integration of lean and 3D printing, the work in this field is still insufficient. And generally speaking, this integration is still overlooked even in other sectors [18-19]. Therefore, the current study aims to shed the light on this area by investigating how lean principles can be applied in the construction 3D printing processes.

2 Lean Theory and 3D Printing

The theory of lean originated in Japan following the development of the Toyota Production System (TPS) [20]. Following World War II, Toyota faced various challenges such as the scarcity of raw materials, low productivity levels, and the need to meet the diversity in the demand by the Japanese customer. These challenges raised awareness toward achieving a zero-waste production system [21]. The new production system helped Toyota to benefit from the advantages of craft production and mass production at the same time without being affected by the high cost of the first and the rigidity of the second [22]. It also helped Toyota to achieve remarkable success to the limit that it was labeled as “The Machine that Changed the World” in the book of Womack et al [23]. This success was key to improving many production systems in various countries and several sectors including the construction sector [24].

Value creation based on the client’s need and requirement, value stream mapping, creating flow, establishing pull, and achieving continuous improvement are the main principles of the lean theory [25]. Creating flow means that the production process must flow smoothly and all the bottlenecks that hinder should be eliminated [26]. These bottlenecks are defined as wastes. Taiichi Ohno; the developer of TPS presented seven categories for lean wastes in his book "Toyota production system: beyond large-scale production". Recently, two categories were added ("non-utilized talents" and "crises") [27-28]:

1. Defects: examples of defects include producing a defective product or component, failure to meet quality standards, or the need to rework.
2. Motion: this covers unnecessary movement on site or in the workspace.
3. Waiting: delays or wasted time due to waiting for a machine, product, labor, action, decision, information…etc.
4. Transportation: unnecessary movement of materials or equipment.
5. Over-processing: examples of over-processing cover the unnecessary steps in the production or producing something that is not valued or required by the client
6. Overproduction: this refers to producing more than the planned or needed items, producing a product or a component earlier than planned, or ordering too many materials than needed. too early/ ordering too many materials
7. Inventory: Excess storage of materials, Work-In-Progress (WIP), or unused tools
8. Non-utilized talents: Non-utilized crew and skills
9. Crisis: failure to benefit from crisis and opportunities

In construction, 3D printing can offer many opportunities to eliminate wastes when it is compared to traditional construction methods. Lafhaj et al [6] identified a group of factors that contribute to waste elimination due to the use of 3D printing in construction. The factors include:

1. Material management in 3D printing, which helps to reduce unnecessary inventory, WIP, waiting time, and areas for saving final products. This is due to the limited amount of needed materials and the possible direct integration of materials in production.
2. Additive process, which requires no formwork. Accordingly, it reduces the inactive time needed for curing concrete, and formwork time.
3. Automated process, which helps to reduce waiting for labor and unnecessary movement on-site. In addition to reducing rework due to the ability to notice defects earlier than it is in the conventional construction methods. The automated process helps also to avoid overproduction and excess processing wastes.
4. Stable production system, which offers less waiting for crew and logistics.

Nevertheless, similar to any production system, various wastes can be found in the 3D printing processes [6,18-19]. Lafhaj et al [6] listed various possible examples of lean wastes in 3D printing systems such as errors in the design (defects), defects in the robotic system (defects), defective layer (defects), a non-optimal path of printing (motion), waiting for maintenance (waiting), transportation of materials (transportation), too early printing (overproduction), and others.

Apart from the conceptual study by Lafhaj et al [6] that aimed to provide possible examples of lean wastes in the construction 3D printing processes, the authors of this study did not find any study that tried to investigate the presence of wastes in construction 3D printing. Therefore, this study aims to fill this gap and provide an analysis of the found wastes in a conducted 3D printing test.

3 Research Methodology

The main aim of this study is to analyze the lean wastes that may appear during the 3D printing processes. Identifying and removing the wastes in these processes can help achieve improvements and optimize 3D printing.

To achieve this aim, the current study used the following methodology (as shown in Figure 2):

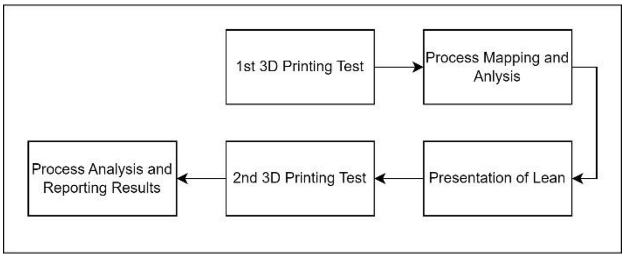

Figure 2. Research Methodology.

3.1 Conducting the first 3D printing test

The test was conducted in a laboratory environment. The team of researchers has previously conducted several 3D printing experiments in the laboratory; however, lean thinking had not been introduced before to these experiments.

As shown in Figure 3, the two tests were conducted to print the same shape. This was to ensure that the results from the tests are comparable.

The printed object has an initial layer in the shape of a hexagon and a final layer in the shape of a circle. Between the first and final layers, the trajectory twists from one shape to another, creating an object impractically constructed with traditional methods. The printed object has a diameter and height of 45 cm, a layer height of 1 cm, and a layer thickness of 5cm. The overall printing time is supposed to be 15 minutes and 34 seconds and the overall volume of concrete is 132.32 Liters.

1st Test 2nd Test

Figure 3. Printed object.

3.2 Process Mapping and Analysis

Process mapping aims to understand and register all the process steps and sub-tasks to understand the value-adding activities (VA) and the non-value-adding activities (i.e. wastes or NVA) [18]. The team divided the overall process based on 17 main steps starting from the preparation of the printing materials (following wearing personal protective equipment) to the end of the printing process.

Using video recording during the two tests, the process was mapped and analyzed in a standardized structure that is shown in Table 1. This structure was for the two parts of each test; the materials and robotic parts.

Using the mapping and analysis structure, each task was decided if it is necessary (VA) or unnecessary (NVA). The time of each task was defined and each NVA task was assigned to the waste category it belongs to. Following the mapping of the tasks, the analysis was conducted to identify the overall wasted time and the percentage of each waste category.

Table 1. Process mapping and analysis structure.

No.	Time	Task description	Type (VA/NVA)	Category (if NVA)
Task 1	t_1	Searching for a tool	NVA	Motion
Task 2	t_2	…	…	…
…	…	…	…	…
Task n	t_n	…	…	…

4 Results

4.1 The first test

The analysis of the first test revealed that the overall time to print the selected object was 2785 seconds and the total wasted time was 678 seconds. In other words, 24.34% of the printing process was wasted on non-value-adding activities.

The analysis also showed (as shown in Figure 4) that 45% of the overall wasted time was due to the occurrence of waiting activities, 22% was due to transportation activities, and 19% was because of the unnecessary movement or motion activities. For the robotics part, the percentage of the waiting activities was 55%, and then 14.53% and 13.70% for the transportation and motion activities, respectively. The highest percentage for the materials part was for the transportation activities (32.25%), then for waiting (29.22%), and then for motion (26.62%).

Examples of the NVA activities include waiting for information (waiting), searching for the design file (waiting), waiting due to technical error (waiting), searching for a tool (motion), searching for materials (motion), transportation of the mixer (transportation), redo weighing of materials (defects/rework).

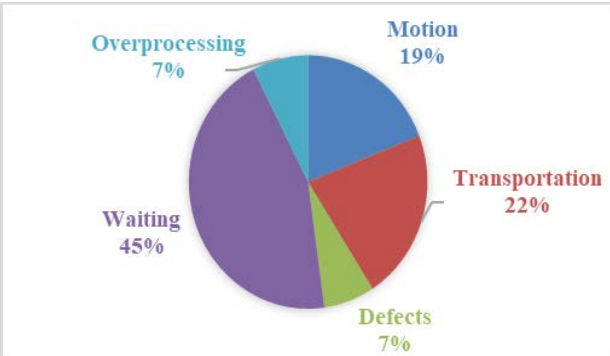

Figure 4. Percentages of waste categories activities to the overall NVA activities in the 1st test.

4.2 Presentation of lean

Following the analysis of the first test's results, lean principles and tools were introduced to the team. The presentation included introducing the principles of lean and lean construction and reviewing the wastes found in the first test. The presentation also covered some tools that can be helpful when trying to improve the 3D printing process and eliminate the found waste. The tools that were covered were:

- 5 Why: "is a systematic questioning process used to identify the root cause of a problem" [29]. This tool was used to explain the occurrence of lean wastes found in the first test.

- Value Stream Mapping (VSM): one of the main principles and tools of lean, where the process is mapped and visualized to show the value flow along the different activities, and as a result, finding rooms for eliminating wastes and optimizing adding value activities [29-30].
- 5S workplace organization: a structured method to achieve, maintain and improve workplace organization and standardization aiming to ensure having a safe work area and efficient processes with the least amount of waste [29]. 5S is based on five actions that start with the letter “S”, which are “Sort”, “Set”, “Shine”, “Standardize”, and “Sustain”.
- Plan-do-check-act for continuous improvement (PDCA): a four-step iterative structured method to achieve continuous improvement by testing gains in the process improvement when taking different actions. In this method, Plan refers to (set up a plan and expect results), Do refers to (execute the plan); Check refers to (verify anticipated result achieved); and Act (evaluate; do it again) [29-30].

In addition to discussing some solutions such as the supermarket solution, Visual Management (VM), predictive maintenance, error-proofing, and parallel processing.

4.3 The second test

Following the lean presentation, the team decided to take some measures to improve the 3D printing process such as the use of supermarket, workplace organization, and parallel processing. Other measures were decided to be adopted in the future due to the time limitation and the need to conduct more than one test to validate their use. Examples of these measures include visual management, error-proofing, and predictive maintenance.

The analysis of the results of the second test revealed that the total time was reduced by 152 seconds (total= 2633 seconds) in comparison to the first test. The total wasted time on NVA activities was 13.1% of the overall process time.

Figure 5 shows the percentages of the waste categories activities to the overall NVA activities. The figure shows that waiting activities remained to be the most frequent activities in the second test constituting 51% of the overall NVA. The percentage of the waiting wastes was mostly in the robotics (65.77%), while in the materials part was 16.6%. Following the waiting activities, motion (23%) and transportation (15%) remained to be the highest.

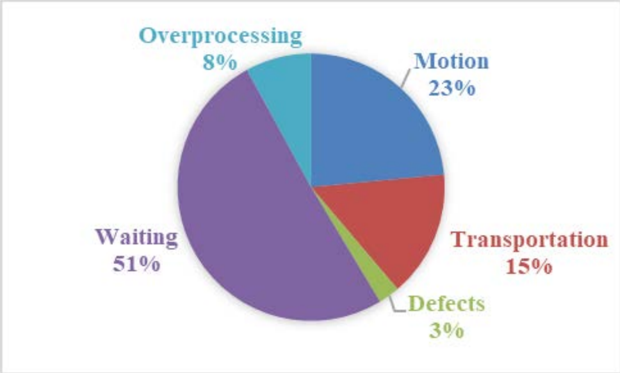

Figure 5. Percentages of waste categories activities to the overall NVA activities in the 2nd test.

Figure 6 shows a comparison between the number of NVA activities in the two tests. The Figure shows a decrease in all categories. The highest change was in the transportation activities and the defects/rework activities. This might be attributed to the workplace organization and parallel processing work that helped the team to avoid doing too many transportation activities or doing the same thing twice.

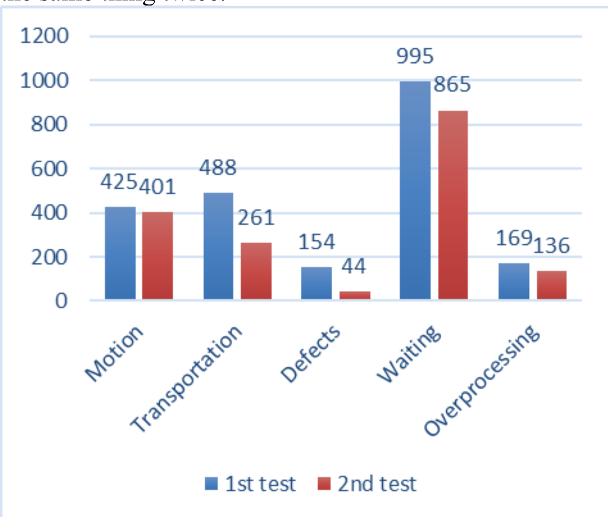

Figure 6. Percentages of waste categories activities to the overall NVA activities in the 2nd test.

Despite the decrease in the waiting and motion activities, there is a need for more work to ensure achieving the continuous improvement goals, delivering higher value, and eliminating more waste. This might be done by improving the planning of the process and workplace, use of visual management, and improving the coordination work.

5 Discussion

Lean thinking and 3D printing are two of the most important concepts in the modern construction environment. This is because the two concepts have shown numerous potentials to revolutionize the construction sector in many ways including efficiency improvement, saving time of construction, improving quality, achieving client satisfaction, and achieving sustainability [31-33]. Nevertheless, the integration of the two concepts together has not been sufficiently covered. The current study, which is based on two-phase laboratory investigations tries to achieve this aim by analyzing the found lean wastes that affect the flow in the 3D printing processes.

The results of the first test showed that more than 24% of the 3D printing time was wasted on non-value-adding activities. According to Aziz and Hafez [34], the average wasted time in manufacturing operations is around 12%, while it is more than 57% in construction projects. Despite the need for many other investigations, the found ratio in this study may support the claim that 3D printing can help reduce wasted time in construction operations. However, this ratio is still high and calls the need of further thinking about possible ways to improve 3D printing operations' efficiency.

Following the presentation of lean, the ratio of waste was reduced to 13.1%. This showed a possible opportunity to improve the time and even the cost of 3D printing systems while maintaining the quality or even improving it, which is the essence of lean thinking.

In the two tests, the percentage of waiting wastes was the highest among the non-value-adding activities. The same behavior was reported in different cases in the traditional methods of construction [35-36]. As a result, similar to the traditional construction methods, 3D printing systems should be built over a high level of coordination and can benefit from different lean tools (e.g. JIT, VM, and pull planning) to eliminate as much waste as possible. It is worth mentioning here that as the current study was conducted in a laboratory environment with a known mixture and known test parameters, other sources of waste may appear while constructing a full-scale 3D printing building. One main example of these wastes is the "defects", which was not the highest in this study but according to Sini et al [12], it is the main reason why 3D printing is still immature enough to guarantee the quality of the 3D printed products. Accordingly, it is recommended to conduct similar investigations to answer the same research questions in a real project environment, where other factors such as supply chain and logistics management can be covered.

6 Conclusions

The current study presents an example of employing lean thinking to improve the performance of 3D printing systems in construction. It also shows that the two concepts can be integrated to maximize productivity in this sector. This study tries to fill the gap in the literature that lies in the scarcity of resources about this integration. It also serves as an example of how to analyze and identify wastes in 3D printing operations. As a result, this study tries to provide practitioners and researchers with a way to investigate how to improve efficiency in the construction of 3D printing.

In addition to the lab investigation, the current study has the limitation of the number of tests. While continuous improvement is one of the core concepts of lean, the current study builds its results over a short period of investigations. As a result, there is a need for a larger number of tests and a longer period to ensure achieving greater improvement and eliminating the possible wastes that may appear over time. Other research areas can cover investigating the lean wastes or lean adoption opportunities in onsite and offsite construction 3D printing systems, exploring the challenges that face this adoption, examining the impact of lean on supply chain management and sustainability in the two types of systems, and using other construction 4.0 practices side by side with lean to improve the performance in 3D printing operations.

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