Chapter 15
Conceptual Study and Literature Review of Integration of Lean Manufacturing and 3D Printing in Construction to Support Sustainability

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Abstract This chapter presents a literature review and conceptual study of 3D printing of concrete in lean and sustainability perspectives. Three research questions are addressed. (1) What are expected challenges in practical applications of 3D printing of concrete; (2) To what extent can 3D printing of concrete support lean construction principles; (3) What are possible sustainability implications from applications of 3D printing of concrete in the construction sector? On the first question, we find that there are still a number of challenges that need to be addressed to move 3D printing from test sites to integrated use in construction projects. The integration of a 3D printer in the building process is then investigated using scenarios; façade elements and self-insulating wall elements. On the second question, we find that lean techniques provide for coordination and good information flow. If the information flow and planning process is taken care of in this manner, 3D printing can be successfully integrated into most larger construction processes and sup-

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port sustainability in the construction sector. Regarding the third question, 3D printing can contribute to achieving several UN Sustainable Development Goals (SDGs), for example through the reduction of waste and more efficient use of natural resources, which is also related to the objective of lean construction. This means that lean appears to be a suitable approach for sustainable construction, and this paper discusses how 3D can be used as a technology to support the ambition of moving the construction industry in a more sustainable direction.

Keywords Additive manufacturing · 3D-printing · Lean · Construction

15.1 Introduction

This paper studies the use of three-dimensional (3D) printing in construction projects from a lean perspective. In the construction industry, additive manufacturing has emerged as an interesting option that can change how projects are done. As a consequence of the current movement toward digitization and automation, the industry is under pressure to re-think and renew its use of technology (Olsson et al., 2021).

3D printing is a type of additive manufacturing. Additive manufacturing relates to the process of joining materials to make objects from 3D model data, usually layer upon layer (Dietrich et al., 2019). Synonyms include additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and free-form fabrication (Astm f2792).

Since 2015, the UN has sought a more desirable future in 17 areas of concern, called Sustainable Development Goals (SDG). Additive manufacturing aims to contribute to several of these. 3D printing is actively contributing to SDG 9 (industry, innovation, and infrastructure), which aims to upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities. 3D printing is relevant also for SDG 12 (Responsible consumption and production) which aims to achieve sustainable management and efficient use of natural resources. In both cases the contribution of additive manufacturing is through a reduction of waste and more efficient use of natural resources, achieving a transition to more sustainable construction methods. There is a growing trend in the use of more sustainable building materials and systems, so that in the construction sector, additive manufacturing may be displacing other construction systems with similar technical characteristics but with worse environmental values. As pointed out by Francis and Thomas (2020), lean and sustainability have common goals of promoting resource efficiency and reducing waste.

The purpose of this paper is to analyze 3D printing in a lean perspective and to discuss practical applications of 3D printing of concrete in the construction sector. The three research questions (RQs) of the study are:

RQ1. What are the expected challenges in the practical applications of 3D printing of concrete?
RQ2. To what extent can 3D printing of concrete support lean construction principles?
RQ3. What are the possible sustainability implications from the applications of 3D printing of concrete in the construction sector?

15.2 Applied Method

This study was performed as a part of the EU-funded research project HINDCON. To begin with, an extensive literature review was done on practical experiences from 3D printing of concrete for applications in the construction sector. This search included sustainability aspects. Lean construction and lean principles in general were known to the authors form before, but the literature search included a special focus on lean and 3D printing.

The paper uses two scenarios to illustrate how the construction sector can be affected by the implication of such technology: façade elements and self-insulating wall elements. The building elements used in the scenarios were all selected based on a workshop in 2016 concerning the applicability of 3D printing techniques. The discussion concerned building elements where the use of 3D printing techniques could realize elements with additional or better properties. The workshop resulted in a list of building elements that may be produced with the HINDCON printer and where this technology is likely to find usage. The paper also utilizes work in the HINDCON project especially targeted on sustainability considerations of the applied 3D printing technology.

15.3 3D Printing of Concrete

15.3.1 Additive Manufacturing with Concrete

Guaman-Rivera et al. (2022) found ongoing experimentation with 3D printing in construction and challenges related to the readiness of the technology. Currently, there are three large-scale additive manufacturing processes targeted at construction and architecture in the public domain, namely Contour Crafting, D-Shape, and Concrete Printing (Lim et al., 2011). All three have proven the successful in the manufacture of components of significant size and are suitable for construction and/or architectural applications. Contour crafting and concrete printing are both extrusion techniques while D-Shape is more like normal printing where a binding agent (water) is printed/sprayed onto a bed of compacted cement mix powder.

Concrete printing is based on the extrusion of cement mortar, and the process has been developed to retain three-dimensional freedom and has a smaller resolution of deposition, which allows for control of internal and external geometries.

15.3.2 Printing Structural Elements in Concrete

The setting or hardening of concrete is a chemical process that takes time. Maximum strength of concrete is usually considered to be the strength it has attained after 28 days of curing, but how fast the curing process is depends on the type of concrete and additives. For 3D printing purposes, it is important that the concrete retains shape after extrusion and cure fast enough to carry subsequent layers without deformation. On the other hand, the time between printing subsequent layers may decrease the strength of the bond between layers significantly, due to curing of the surface of the deposited layer. There is a time window for depositing a new layer depending on the stability of the previous layer due to rheological behavior and the fast concrete cure, enough to bear the weight of the new layer, and the time until the previous layer becomes less chemically active and thus result in a weaker bond. Experimental testing by the Eindhoven University of Technology (Salet et al., 2017) suggests a framework of three components (printable concrete, 3D printer, and print geometry) for describing a 3D concrete printing (3DCP) system where each of these components constitutes a range of parameters and variables.

Bos et al. illustrate the interdependencies of the components in a 3DCP system (Bos et al., 2016). They describe that the buildability of layers is limited as new layers add weight on top of the structure and thus depend on the stiffness and strength of the printed green layers. Fast-setting concrete mixes can eliminate this problem.

A simple straight stacking of layers is complicated. Cantilevering layers represent another type of problem with 3DCP. The contact surface between extruded strings (Gosselin et al., 2016) is another issue. In spite of this, 3D printing is interesting.

In 3D printing, the design, material, process, and product properties are recognized as interdependent. This interdependency is more pronounced when 3D printing in concrete, due to the slow setting reaction of concrete (Bos et al., 2016).

15.3.3 Reinforcing 3D Printed Elements

Concrete as a material has high compressive strength and low tensile or ductile strength. For most types of structural elements concrete needs reinforcing with other materials. Traditionally this is done by building a frame in rebar steel and casting concrete around it. Adding glass, steel, or carbon fibers to the concrete mix as well as some other additives may reduce the need for reinforcements, but these additives increase the cost of the concrete, and fibers increase the difficulty of pumping. There are also reported trials of embedding steel wire in the printed concrete layers to increase ductile strength.

With today's technology, there seem to be three different options for making structural elements in 3DCP:

- Limit the use of 3DCP to compression-loaded elements such as domes, arcs, and straight decorative columns.
- Use 3DCP to print an outer shell for the structure to be used as a mold/lost formwork. The shell will then be filled with traditional reinforcement and concrete and the shell is integrated into the structure.
- Print the structure with reinforcement integrated into the element on the *x*/*y* plane (horizontal at printing) and leave holes to be filled with tensioned steel wire or a rebar/concrete mix along the *z* axis (vertical).

15.3.4 Production of 3D-Printed Elements

The cycle time of the printer will in most cases be less than the curing time of the concrete. Effective use of the 3D printer then dictates that the printed structure must be moved after finishing printing (or the printer must be moved). This implies that the printed element must have cured adequately to withstand vibrations and small shocks in the movement without deformation.

At the building site, the finished 3D-printed structural elements will usually need to be lifted in place. The use of lifting equipment will introduce stresses to the elements other than the forces that will be working on it in the final assembled position. Unless the elements are left to be fully cured before assembly, it is thus necessary to evaluate the strength of the structure while it's not fully cured and with respect to other forces than it will be subjected to in the final position. The alternative is to set aside time to allow the elements to fully cure before assembly.

15.3.5 3D Printing and Sustainability

There are several potential advantages for 3D printing in a sustainability perspective. Environmental impact can be reduced by minimization of material waste, which is of particular interest, given the high carbon footprint of concrete. 3D printing can produce less waste and use less materials (Rael and San Fratello, 2011; Berman, 2012; Achillas et al., 2015). Additive construction such as 3D printing can also reduce emissions related to transport (Achillas et al., 2015; Strauss, 2013).

Muñoz et al. (2021) did a life cycle assessment (LCA) on a concrete 3D printing system. Their study included a complete supply chain of the 3D printing equipment, operation, and end-of-life, based on real data from a demonstration plant installed in Spain. The results showed that 3D printing can have a lower environmental impact than traditional construction for small production series. If the same structure needs to be produced in larger volumes, their results indicated that 3D printing and traditional production have a similar environmental impact.

15.4 Lean Construction

Lean construction (LC) is the continuous process of eliminating waste, meeting or exceeding all customer requirements, focusing on the entire value stream, and pursuing perfection in the execution of a constructed project (Diekmann et al., 2004). LC principles represent the implementation of major concepts to drive changes, such as increasing transparency and defining the value stream. The literature contains a number of attempts to define lean principles for construction (Koskela, 1992, 2000; Koskela & Howell, 2002; Höök & Stehn, 2008; Towill, 2008; Jørgensen & Emmitt, 2009).

The synthesis of these studies results in the following set of lean construction principles: (1) define and deliver the value for customer systematically; (2) reduce complexity and variability; (3) eliminate non-value-adding activities; (4) achieve continuous process flow; (5) increase the output flexibility; (6) continuous improvement and knowledge building; and (7) leadership for lean implementation.

15.4.1 Lean Construction Processes

Construction projects consist of several phases, including project design, product design, process design, procurement, and on-site installation (Ballard, 2008).

The first phase, project design and planning, includes alignment of customer and stakeholder purposes, definition of the project, concept design, and planning of the activities. Lean projects are structured and managed as a value-generating process for customer, with minimized number of steps. Activities are synchronized through all steps, focusing on flow as opposed to productivity.

The second phase, lean product and process design deal with aligning product and process design, considering the alignment of values, concepts, and criteria. Lean design actively involves the client, user, stakeholders, and suppliers. Value and waste consequences of decisions are made transparent at the design stage, exploring alternative solutions with maximum design space flexibility.

The third phase, Lean procurement and supply chain management, consists of detailed engineering, fabrication, and delivery of materials. Lean procurement includes principles such as establishing a supply network at the best value for the customer, reducing purchasing and supply lead times, simplifying material management processes, and pulling materials from the supply network as needed from the workplace.

Finally, lean construction/ assembly/on-site installation begins with the delivery of the materials and information to the site and deals with the on-site installation of materials, completing the construction, and commissioning. Lean assembly aims to standardize the work and quality of the outcomes on site.

15.4.2 Lean Construction Tools

Tools allow the implementation of principles, such as the use of information-sharing indicators and safety instructions. In this section, the term tools also incorporate methods, practices, and techniques. Different tools address different principles at different phases of the projects. Chief Engineer System (Morgan & Liker, 2006) facilitates the lean principle of defining and delivering the desired value for customers, by front-loading and involving the customer at the product development phase.

Last planner system (LPS; Ballard, 2000) aims to eliminate the non-value-adding activities, by introducing a pull-based production control system at the construction site. A big room (or Obeya room) that gathers all the important information from a project and supports knowledge building and sharing (Oppenheim, 2004) is an example of tool that supports the principle of continuous improvement and knowledge building. Takt time control (Duggan, 2013) in make-to-order industry a bottleneck activity is often chosen (or even made) to control the output from a production line. The Takt is simply defined as the desired output from the activity divided by the time to make one unit. By placing this bottleneck late in the value chain two things are achieved: a predictable rate of output from the production line and a focal point for the coordination of inputs.

According to Carvajal-Arango et al. (2019), the implementation of lean construction practices can have positive effects on all three dimensions of sustainability; economic, social, and environmental. They point out that several of the established lean construction practices have documented positive effects in the three dimensions of sustainability. Related to 3D printing, those of particular interest include modular construction, BIM, and Concurrent Engineering. El Sakka and Hamzeh (2017) applied the lean construction tool value stream maps to compare 3D printing with traditional production and found a 60% reduction in lead time, along with reductions in cost, reduction of waste, and improved quality.

15.5 Case Illustration of Manufacturing and Logistics Flow for 3D-Printed Structural Elements

3D printing offers great advantages to traditional place-built formwork and prefab elements when it comes to relatively cheap and effective customization of building elements. Compared to place-built one-of-a-kind structures this new technology offers customization at a lower cost by either printing the formwork in support materials or by integrating the formwork in the structure. On the other hand, the lead time of a 3D printed structural element that first must be printed as a shell, cured, filled with reinforced concrete, and cured again, will be substantial. The cost and properties of the elements will depend on what materials are used but can generally be thought of as more expensive. With the relatively long lead time from manufacturing the element to assembly, lean production governed by pull mechanisms is also not easily achieved. The following is a discussion of the industrial application of 3D printing to four different building elements that are used for illustration of the applicability of 3D printing.

15.5.1 Façade Elements

The ability to make freeform creative elements without costly formwork makes 3D printing in concrete an obvious choice for façade elements. 3D printing also offers new opportunities compared to prefab elements in that these façade elements may be unique without adding additional costs. However, facade elements often have double functions in that they in addition to being aesthetically pleasing also is part of the building load-bearing structure and also provide the building with thermal and acoustic insulation and the necessary protection against external weather conditions, and also the transmission of other loads such as wind. Façade elements thus often need to be reinforced to have the necessary tensile/ductile strength. The necessary strength may be achieved by leaving holes in the printed element and filling these holes later with either tensioned wire or reinforced concrete.

The cycle time of the printer for printing large building elements will for practical purposes be shorter than the curing time of the same elements. This implies that the printed elements need to be moved from the printer before they are fully cured to free up the printer for other tasks. On the other hand, moving "green" elements represent the risk of deformation due to shocks and/or vibrations. To reduce this risk, the elements should be printed on pallets that may be moved by shock-free transport equipment. Heavy lift equipment of this type is available and in use in shipyards.

Another consideration concerning the strength of the façade elements is stresses during lifting into the final position. These are different from the forces the elements will be subjected to as part of the building. It's also likely that lifting may take place while the concrete is not fully cured due to variations in curing time due to external factors like weather, temperature, and humidity. The standard way of designing with all stresses accommodated by the reinforcement will also work with 3D printed elements but may limit the artistic freedom in designing the elements as the openings in the form must be available for reinforcement after printing.

All issues described above will cause long lead time, which makes the production process not very suited for lean thinking. Just-in-time delivery of the element to the building site must be initiated long before delivery and cannot accommodate late changes in the design. Some time may be saved in the process if the design of the element can use tensioned wires as reinforcement.

On the other hand, the production process for façade elements represents an efficient way of creating unique building features that would take costly and time-consuming formwork to produce in any other way. Precast elements are usually standardized for obvious reasons and place-built forms/scaffolding are both costly to erect and sometimes dangerous to fill. Some reports that 50% of the building time and cost of new building is formwork and reinforcement. Using 3D printed items as lost formwork for a one-of-a-kind precast façade element will thereby be a more efficient way with respect to today's technology.

15.5.2 Self-Insulating Wall Elements

The wall elements discussed here will not be load-bearing. Load-bearing walls imply reinforcement by rebar or other high tensile/ductile materials. Walls may be printed as lost formwork and also for load-bearing walls, but such elements will not be self-insulating as they will be filled later with reinforced concrete.

The idea behind a self-insulating wall is to leave enclosed air in the structure to provide insulation. Insulation may be achieved by leaving empty space between an inner and outer wall or fill the space with other insulating material. In both cases, the inner and outer walls need to be connected in a way that does not leave thermal bridges but holds the wall elements together. One way of achieving this is to print a third surface inside the outer layers that connect to the inner and outer walls at alternate points. This way the thermal distance between the inner and outer walls will be greater than the distance between the surfaces of the element. Gosselin et al. (2016) describe how a slight change in designing how inner and outer walls are separated can reduce heat transfer by 58% in their example.

The advantage of printing wall elements rather than using pre-cast elements lies in the possibility of curved surfaces and other integrated design elements in the structure of the wall. Precast elements are usually made lying flat on tables that are flipped over when the first surface is cured before the next surface is cast. The connection between the two surfaces is usually made by rebar steel which is also employed for lifting purposes.

The technique of 3D printing wall elements in concrete opens new possibilities in architectural design. Using traditional methods curved surfaces are costly and take a long time to make. Decorations and ornaments integrated into the walls also imply place-built molds which similarly add time and costs. With 3D printing, the process of making a curved and ornamented wall is the same as a straight wall. As an added benefit, the wall can be made self-insulating in the same process.

The production process, however, must include time for curing. The wall elements must be made sometime before they are assembled. Changes or other events that may happen while the element is curing will thus lead to rework. All these issues again make it difficult to implement lean principles.

15.6 Discussion

The ability to produce building elements directly from 3D model is possibly the most attractive feature of 3D printing in concrete. This opens up for almost zero-material waste in the production. This is well aligned with the philosophy of lean construction, which is based on strategies to reduce all types of waste in production, time, and effort. The basis for 3D printing and lean construction to support sustainability in construction is therefore in place.

There are, however, still two limitations to 3D printing of concrete that are not resolved by today's technology that inhibit working directly from BIM models. The first obstacle is the inability to reinforce the elements in all directions. As has been pointed out earlier, only reinforcement along the printed concrete strings is possible today whether this is done by adding fibers to the concrete or embedding wire in the concrete strings. For reinforcement in the vertical plane (when printing) holes must be left in the structure to be filled by either reinforced concrete or post-tensioned steel wires.

Post-tensioned wires need to be mounted in brackets supported by concrete that have achieved high compression strength. The throughput time of a structure printed this way will thus include time for the curing of the concrete. The curing time for the printed concrete will vary depending on the type of concrete and additives.

The other obstacle is that holes or channels in the horizontal plane need to be closed at the top. Unless the diameter of the hole or channel is small compared to the width of the printed string, this is difficult to achieve without support. A possible solution may be to print clay in the hole or channel that may be washed out when the concrete is set, but that implies a second extruder with a change of extruder for each layer to be printed. Another solution could be to insert supports when the channel or hole is closed. The hole or channel would then be square at the top.

The best way is probably to print technical wall elements with most channels or holes in the vertical plane. Some wall elements may then be printed with layers that are vertical in the final position. Unless the wall element is supposed to take up some tensile/ductile forces, this will probably not be a problem. The maximum ductile/tensile strength of the element is limited anyhow both from the limited possibilities of including reinforcement along the layer and because of the possibility of layer separation with no reinforcement between layers. Technical wall elements that need tensile/ductile strength are likely to be produced by using the 3D print as lost formwork that is filled with reinforced concrete after curing.

Efficient use of the 3D printer presupposes moving elements out of the printer before they are cured. As wall and wall elements are relatively thin and high and thereby unstable, moving "green" elements is an added risk. A longer curing time in the printer, thus increasing the cycle time of the printer, and/or extra transport supports might be needed. The lead time from starting printing the element to assembly will anyhow include time for curing as the element should be cured before assembly. Filling the structure with reinforced concrete to achieve tensile/ ductile strength will add time as the printed form need to cure before filling. Unfortunately. a long lead time from start production to finished element means that the process does not lend itself easily to lean production.

Carvajal-Arango et al. (2019) found only few papers that directly related lean construction to sustainability. Adaloudis and Roca (2021) identified some challenges from a sustainability perspective because their findings indicated that incentives to invest in 3D printing were not mainly related to the environmental benefits, but rather to the technology's potential to increase automation and thereby moderate a shortage of skilled labor in the construction sector.

15.7 Conclusions

In the following, we address the defined research questions of the study.

15.7.1 Expected Challenges in Practical Applications of 3D Printing of Concrete?

Our first research question addressed what challenges that can be expected in practical applications of 3D printing of concrete. While 3D printing and other types of digitalization have the potential to change the construction project process, there are still a number of challenges that need to be addressed to move 3D printing from test sites to integrated use in construction projects. This paper has studied such a change of projects in a lean perspective.

The main attraction of 3DCP is the possibility to produce almost any shape without first building a mold or form for the concrete. Formwork and reinforcement in a modern building are reported to account for up to 50% of the building time and proportionally high costs. Being able to "disregard" the costs of nonstandard shapes will in addition give architects greater freedom in how they design new building artistically.

However, as described by Salet et al. (2017), 3D printing is a process between the 3D printer, the printable concrete, and the architectural design. At present, there exists some knowledge of what can be printed but how the design may limit or extend these printing capabilities is still unknown. By integrating fibers in the concrete mix some ductile strength may be achieved along the direction of the extruded concrete. At present this limits in most cases the use of 3D printing applications to create "lost formwork" or molds to be filled with reinforced concrete.

Printing time and to some extent also curing time depend on the size of the element. The production time on any element will depend on what is being made and, as pointed out by Bos et al. (2016), there exists an interdependency between the material, printing process, and design that introduce uncertainty to estimates.

15.7.2 3D Printing and Lean Construction Principles

Our second research question relates to how and to what extent 3D printing of concrete can support lean construction principles. Lean production focus on flow and just-in-time delivery. As printed concrete needs to mature before use, it is not well suited for lean thinking. There will always be a delay between producing the element and assembling the structure This means that the design must be finalized before starting a print and will not accommodate changes without rework.

The complexity of integrating the production with a 3D printer in the building process demands robust and versatile planning and control. The principles and tools of Lean construction (Moujib, 2007) may support this role. The hierarchical structure of the Last planner tool for long-, mid-, and short-term planning combined with the pull-based start of production renders integration with the current situation in the building process possible. Lean construction techniques can provide for coordination and good information flow. Provided that the information flow and planning process is taken care of, 3D printing may be integrated into most larger building processes, which probably will be needed to deliver the potential sustainability benefits.

A 3D printer is typically aimed at producing unique elements, so buffer stocks of standard elements are not possible. In fact, a 3D printer is close to the lean ideal with little or no changeover between different products. Emphasis is thus needed on production planning and control. The recommendations are to make use of the concurrent engineering methodology combined with the lean practices, a broader scope on each of the phases in the construction process, and information hubs and big rooms (Aasland & Blankenburg, 2012).

15.7.3 Sustainability Implications from Applications of 3D Printing of Concrete in the Construction Sector

Finally, the third research question addresses possible sustainability implications from applications of 3D printing of concrete in the construction sector. The reduction of waste is a key sustainability argument in favor of 3D printing. It is documented in previous studies that a 3D-printed object can have a lower environmental footprint, compared to traditional construction processes. 3D printing can contribute to achieving several UN Sustainable Development Goals (SDGs), including SDGs 9 and 12. One key contribution that aligns well with lean philosophy and supports sustainability is a reduction of waste and more efficient use of natural resources. However, this and previous studies indicate that the 3D printing technology is still relatively novel, and it may still take some time until it makes significant contributions to a more sustainable construction industry. But we need to work to get there.

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