A Lean-based Production Approach for Shotcrete 3D Printed Concrete Components

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Abstract –

Additive Manufacturing allows for high geometric freedom and the fabrication of non-standard building components. This new-found flexibility results from the fact that no formwork is required with additive manufacturing and thus each part can be different at no additional cost. One drawback however is that the geometric freedom comes at the price of non-verified geometric precision, requiring methods to determine and possibly counteract deviations and ensure building component's quality. Within this paper we present an "Lean-based Production Approach" for an off-site production of concrete components. Therefore, firstly lean construction is introduced and its synergies with additive manufacturing are shown. Shotcrete 3D Printing is used as a case study and illustrates the approach and unveils current potentials and challenges. Our approach is mainly based on an on-demand production, bi-directional digital workflows and quality checks. Current methods for geometric and surface quality as well as for predicting production (and process) times for varying components still need to be developed further. We conclude with forecasting a new and more intelligent production system in construction.

Keywords –

Additive Manufacturing, Construction, SC3DP, Prefabrication, Lean Construction, Quality Control

1 Introduction

In the context of a social rethinking and political ambitions to produce in a climate-neutral and resource-friendly way, the construction industry, as one of the largest industrial sectors in the world, is of particular importance. The construction industry is mostly confronted with the challenge of the "large scale" of the structures to be built [1]. Additional challenges result from typical construction industry peculiarities, such as one-off production, on-site production, or engineer to order production [2]. Furthermore, construction is usually done on a project basis, where a considerable number of independent companies are linked only by the goal of delivering building. These construction peculiarities are often blamed for the construction industry's poor project delivery, i.e., construction delays and exceeded budgets as well as the contribution concerning waste and value loss [2].

To counteract stagnant productivity and inefficient construction processes, comparisons are often made with stationary production like the automotive sector [3]. It is assumed that similar improvements in the construction can be achieved by adopting established processes and methods from that sector. The goal of a "lean" and value-added production is also increasingly targeted in the construction industry. The traditionally more conservative construction industry has so far found it difficult to implement innovative and, above all, digital and sustainable solutions. However, advances in the field of additive manufacturing (AM) with concrete are opening up new construction process options and production principles [4]. In particular, Shotcrete 3D-Printing (SC3DP) as one method of additive manufacturing has the potential to lead to significant improvements in productivity and - hence - to a sustainable production process. Due to the avoidance of formwork as far as possible, a high degree of form flexibility and efficiency gain is achieved, accompanied by new challenges in production with regard to geometric and surface quality accuracy.

The aim of this paper is to show how high-quality precast concrete parts can be produced on the basis of lean principles and to emphasize existing challenges. For this purpose, we will first introduce the basics of lean production and additive manufacturing. Using the SC3DP as an example, an approach is outlined which attempts to solve current production problems.

2 From Lean Production to Additive Manufacturing in Construction

In recent years, the construction industry has developed a greater awareness for the need for a holistic view of the value chain and a process-oriented way of thinking. These developments are driven by several factors, especially current shortcomings such as an extreme fragmentation (of knowledge and project structure) and lack of collaboration within projects. Currently, Lean Construction principles and methods are increasingly being used to restructure (manual) construction processes.

2.1 Lean Production and their principles

The origins of Lean Construction can be traced back to the design and orientation of production (principles) of the Japanese car manufacturer Toyota. During an MIT-study (1985-1991), Womack/Jones/Ross had revealed significant differences from the predominant "buffered production" at that time [5]. The five key lean principles are: (1) define value as what a customer is willing to pay for, (2) map and reduce waste of any kind along the value stream, (3) create a continuous flow for all value-adding steps, (4) produce only on customer demand (pull) and (5) pursue perfection wherever possible. Lean Production aims to produce goods solely in response to demand, rather than mass-produced "in stock." Whereas in the automotive industry high volumes were usually produced based on one (producer-specific) prototype design, buildings have so far and will continue to be unique in most cases based on customer-demand design. Regarding these differences, Lean Production has to be carefully adapted as Lean Construction (LC) within the construction industry.

2.2 Lean Construction

The construction industry is characterized by process instabilities, low added value and waste of various kinds, where the application of different Lean Construction principles and methods promise significant improvements. Due to the traditional project delivery systems and fragmented structures, LC-methods like production cycle planning as well as the “last planner system” are often used, but primarily to improve handcraft production processes. Replication and collaboration are of high relevance for the successful implementation of those two methods to generate stable (but manual) construction processes. In contrast to conventional in-situ construction, prefabrication pursues a higher added value by shifting construction processes to a controlled environment. In order to be economically competitive, avoiding long changeover times and achieving high added value, components and/or their underlying building processes are often standardized on the price of form and production flexibility.

2.3 Towards a Lean-based Production through the integration of Additive Manufacturing in Construction: Lean Construction 4.0

The integration of lean production principles is accompanied by a production "on demand" in an organizational perspective (pull principle). In order to avoid that materials or semi-finished products for subsequent work steps are generated or produced "on stock" contrary to the principles of lean production, components are only supplied just-in-time and only when required. While producing components only on demand and to specific customer requests, generally warehousing and inventory can be minimized. However, the construction industry has produced in nearly all cases only on customer request (“on-demand-production” in a design perspective on the building scale, e. g. unique customer-related building design). Only in specific segments, certain standardized components (e. g. precast concrete girders, columns or walls) have been produced, placed at storage areas outside the factory waiting to delivery to construction site (component scale).

Additive Manufacturing is defined as the “process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” [6]. Hence, Additive Manufacturing seems perfectly suitable to enable a new level of Lean Production on construction sites: Lean Construction 4.0 [7]. The limitations of current standardization approaches could be overcome by AM with concrete since any form can be produced. With AM not the component is standardized but the process, allowing for more freedom of form and a short-term production (hence production on demand in two perspectives). Lean-based additive manufacturing could make it possible to customize every product (flexibility of AM) and to produce without any changeovers in the production line only on demand, as the combination of lean principles and characteristics of additive manufacturing shows:

- **Defining Value.** Value is only what the customer is willing to pay for. Changeover times (of machines and formwork) and the resulting (manual) effort are currently unavoidable to produce different component types (no value-added processes). By using AM, a new level of form flexibility is gained since formwork is no longer necessary resulting in customized or even individualized components based on customers value.
- **Mapping the value stream.** Process analysis of the value chain aims at identifying waste and

unnecessary tasks. Due to additive manufacturing especially formwork as a crucial non-value-adding task can be eliminated. AM makes it possible to produce individually designed components (wall, columns, slabs) without long changeover times focusing on mapping the value stream.

- **Create a continuous flow.** Not only material but also information must be provided in correct order to create a continuous production flow. AM enables both due to a direct transformation of the virtually designed into a physical object making it possible to create a continuous production flow.
- **Establish a pull production.** AM is a fully digitized design-to-construction workflow where the actual production tasks are reduced to “printing”, allowing to produce components promptly on demand (pull), but with a high level of flexibility in form and production eliminating a push production and long inventory times.
- **Pursue Perfection.** Based on necessary 3D-Models for production, robotic-guided concrete deposition prohibits mistakes due to the integrated information flow. Since geometric quality and tolerance aspects are very important, permanent as-planned and as-built comparisons are essential to identify divergences immediately and hence offer a way to pursue perfection of customers value.

3 Additive Manufacturing

Additive Manufacturing is predominately applied in Construction (AMC) for concrete components [4]. Concrete is the most commonly used building material in the construction industry. Considering the climate change and the C02 emissions caused by cement production, the efficient and economical use of concrete is of utmost importance [8].

3.1 Methods of AM in Construction

Additive Manufacturing in Construction (AMC) is suitable both for on-site or off-site application [4]. As known from prefabrication approaches, the desired component quality can be achieved the best, when it takes place within controlled environments [4]. Additive Manufacturing with cement-based mortars, often also referred to as 3D concrete printing (3DCP), means that a component is firstly 3D modelled, sliced into multiple layers and digitally build up layer-wise.

One of the most commonly used AM methods for in-situ application is based on extrusion [9]. In this method, material layers are either extruded from the nozzle in a controlled manner or they flow out of it. This process has a high geometry resolution, but at the expense of a fast application rate [9].

In processes using a particle bed (also referred to as particle bed-based 3D printing (PB3DP)), dry base material (particle or mixture) is placed on a platform (the particle bed) and binder or activator is applied at the required locations according to the desired geometry [10]. The selective application of binder/ activator creates the concrete matrix. This is followed by the build-up of a new layer, starting with the renewed application of the base material to the particle bed. This process is repeated until the component has the desired geometry. After a defined number of printing processes (and layers) the component can be freed from excess, unbound material. The mainly applicable off-site PB3DP process achieves very high resolution and shape accuracy [10].

Shotcrete 3D Printing (SC3DP) is another AM technology mostly suitable for off-site application that offers access to an increase in speed and productivity and in component quality (extra surface finishing needed, see below) [11].

AM allows more freedom of form because it doesn`t need formwork or support structures. However, due to the lack of precision that formwork brings to the traditional process, AM requires advanced methods of quality control, which can be solved through bi-directional (or feedback-based) production workflows. To exemplify this, Shotcrete 3D Printing is described as a case study.

3.2 Shotcrete 3D-Printing

SC3DP has been developed within an interdisciplinary research project at the Digital Building Fabrication Laboratory (DBFL) at the TU Braunschweig [12]. Unlike other additive manufacturing methods, concrete components are built up layer by layer but with the controlled addition of compressed air [18]. It is characterized by high printing speed and varies significantly compared to other additive manufacturing methods with the following aspects [12]:

- Integration of reinforcement: Concrete can be sprayed around structural reinforcement and hence integrate it.
- Surface finish (visual and functional): After the core printing process, shotcrete can be applied robotically as a levelling layer to obtain a higher surface quality. The surfaces can be finished with formative methods if required.

In order to improve manufactured components in the shotcrete 3d printing process – i.e., to produce complex elements with high accuracy in addition to the required surface treatment - the combination of additive and subtractive manufacturing tasks to form a hybrid manufacturing process is a suitable option.

To achieve a decent component quality, the initial printed core is covered with multiple applied secondary layers of shotcrete and in a next task processed with subtractive tools (Figure 1). Compared to common hybrid manufacturing, for example in metalworking, an AM process is combined with a subtractive process here, but additional integration of sensor technology for tolerance and dimensional control is missing. Sensor technology is needed to monitor and validate the increased complexity of the production process [13].

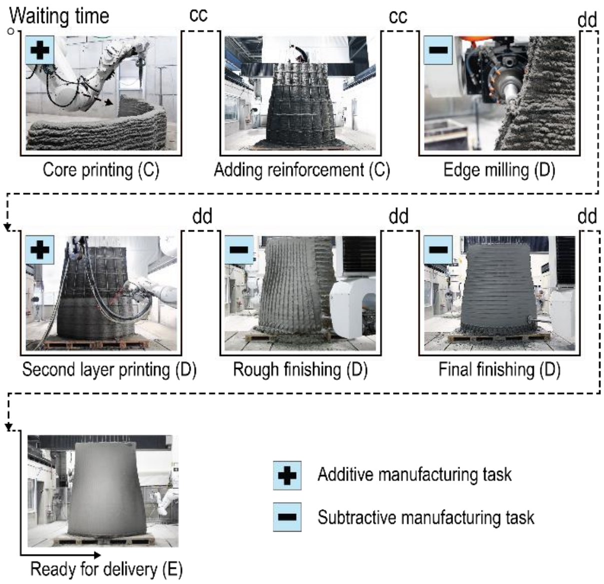

Figure 1: Multiple fabrication tasks for a fully-reinforced double curved concrete component

3.3 Challenges within the SC3DP Process

During these tasks, predicting the behaviour of the printing material is a major challenge. Due to the complex interaction of temperature, forces, material properties, the printing system setup and external circumstances, inaccuracies or even critical errors can occur. The success of the SC3DP and the quality of the component are determined by a large number of parameters to be controlled, such as nozzle distance, spray angle or conveying speed [12] just to name a few.

These parameters have a major influence on the printing quality. Incorrect parameters can lead to a reduction in concrete quality, concrete rebound, varying layer thickness or low early strength. Thus, printing layers can sag over time. Furthermore, the geometrical freedom of the robot tracks is limited due to the low printing resolution. For example, the production of sharp geometric edges is currently not possible using the SC3DP process alone.

Therefore, for high-precision shotcreted parts, a component improvement process consisting of the multiple interlocking tasks (edge milling and surface finishing) and quality inspection (measuring) will be critical in most cases. These interlocking tasks can in turn lead to unpredictable and long cycle times due to repair/finish work or due to insufficient task control.

Currently, SC3DP is characterized by the following challenges [19]:

- Compensation of inaccuracies due to unintended parameter variations during the fabrication process.
- Process validation of different production tasks must take place in order to optimize these tasks.
- Compensation of inaccuracies must be integrated into the manufacturing process. An automated finishing process with subsequent quality control for the surface must be developed to minimize process times.

In order to improve the component quality multiple tasks are needed, which increases the level of process complexity. However, each additional process task may increase the error rate.

Nevertheless, a variety of challenges are correlated with the quality control process as well. Acquiring data for a well-established quality control/check (QC) approach depends on a variety of aspects that could affect the acquisition strategy or the quality. The SC3DP manufacturing environment is in general contaminated. Dust emissions during the production process, coupled with high levels of humidity that occur in the production room, can lead to insufficient data quality (noise) during the data acquisition process. The size and the shape of the object could add another factor for the selection of the sensor as well as the data capturing strategy thus the data does not suffer from occlusion [15].

The material properties of the captured object play a crucial role in the quality of the captured data. After the SC3DP process, the object is saturated. Therefore, for example in case of TLS, infrared wavelength would not penetrate the water surface while green wavelength would have penetration properties through the water column [16]. Moreover, for rough surfaces, the received signal intensity depends on many factors: the distance; the incident angle of a laser beam; environmental and system factors; the value of material reflectance. This material reflectance is influenced by the colour and roughness of the object [17].

In conclusion, selecting an adequate sensor for capturing complete and reliable data depends on inter-correlated factors which have to be investigated thoroughly in order to satisfy the project's requirements.

4 Lean-based Production Approach

It is the aim of research in the project C06 of the Transregio 277 to investigate and develop a production approach for additive manufacturing methods that overcomes current drawbacks such as geometric and surface quality as well as hardly predictable production (and process) times. Therefore, SC3DP is used as a case study for prefabricated components with high-quality (geometric accuracy or surface). The five principles of Lean production are applied as followed resulting in a "lean based production approach (for SC3DP)".

The proposed methodology is shown in Figure 2.

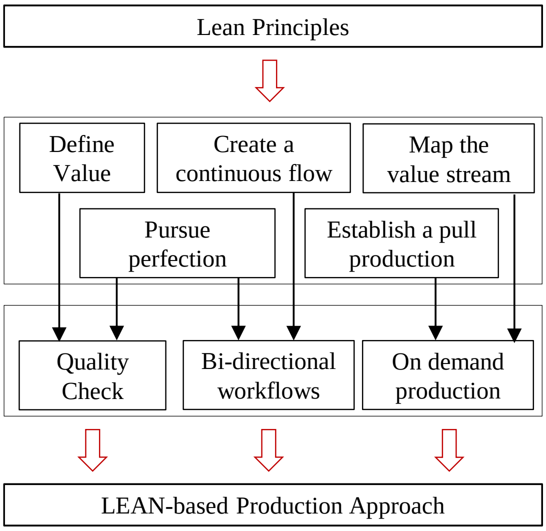

Figure 2: Derivation of the Lean-based Production Approach from Lean Principles

1. **On demand production.** Since with SC3DP technology components can be produced without any long lead time, pull production gets within reach for construction industry. In the context of SC3DP prefabricated components, the construction site ("customer") could communicate the demand concerning individually designed components. This message defines the starting point and the production process begins immediately. Therefore, an on demand production of SC3DP produced concrete components is set up and being discussed.
2. **Bi-directional workflows and quality check.** Short cycles of quality control help to achieve the desired component quality. Due to the lack of formwork and hence lack of precision of AM processes, bi-directional information workflows provide the framework to ensure component quality. Therefore, short continual improvement processes at different stages are presented, e. g. (1) making sure that the core is printed accurately and that reinforcement (if existing) is placed correctly, (2) making sure that the edges are cut precisely and (3) the surface has a high quality.

By applying lean principles to the production and quality control processes, a higher component quality is expected as well as a significant reduction in waste during production and hence a higher productivity. In the following, those parts will be focused in detail.

4.1 On demand production

With the help of a simplified representation of a value stream mapping (Figure 3), the significant production tasks of the SC3DP can be visualized in the context of an on demand production from a holistic point of view [18]. Based on customers demand and a 3D-Model (or a Building Information Modelling (BIM) – Model in the near future) the production of concrete components can be initiated. The SC3DP Process consists of five main tasks: Material Supply (A), Material Production and Handling (B), Core Printing (C), Component Improvement (D) and Delivery (E) to construction site (Customer). Component improvement plays a major role in this process chain since quality control, both of surface and geometric, is crucial for high-quality concrete components as it remains the latest task before the delivery to construction site can start. Hence, it will be discussed further in the following sections.

Value Stream Mappings is a lean production method often used to analyse the production processes. In the context of SC3DP, this technique is confronted with various adaptions. Value stream mappings are very useful to calculate production and process times as well as inventories. However, since with the SC3DP method no geometrical standardized components are produced in series, but rather serialized individual parts, the design-to-construction workflow is nearly the same, but production times vary in each case and every time. The SC3DP method is not limited to one component type (e g. walls or columns). Therefore, a continuous flow might be difficult to create as long as measure times for production and other important process parameters (e. g. printing speed) are not collected within a production database. It becomes obvious that a process and parameter database is a decisive factor of a successful SC3DP Production system. Production and process times (especially of component improvement) heavily depend on targeted geometry and surface quality as well as on curing time. Concrete curing is an important natural process to ensure load-bearing qualities and to allow the transport to the construction site. Aiming a direct design-to-construction-to-assembly workflow, curing times need to be investigated and should be reduced to a necessary minimum. Currently, digital-supervised placement or automated integration of reinforcement is another unsolved challenge.

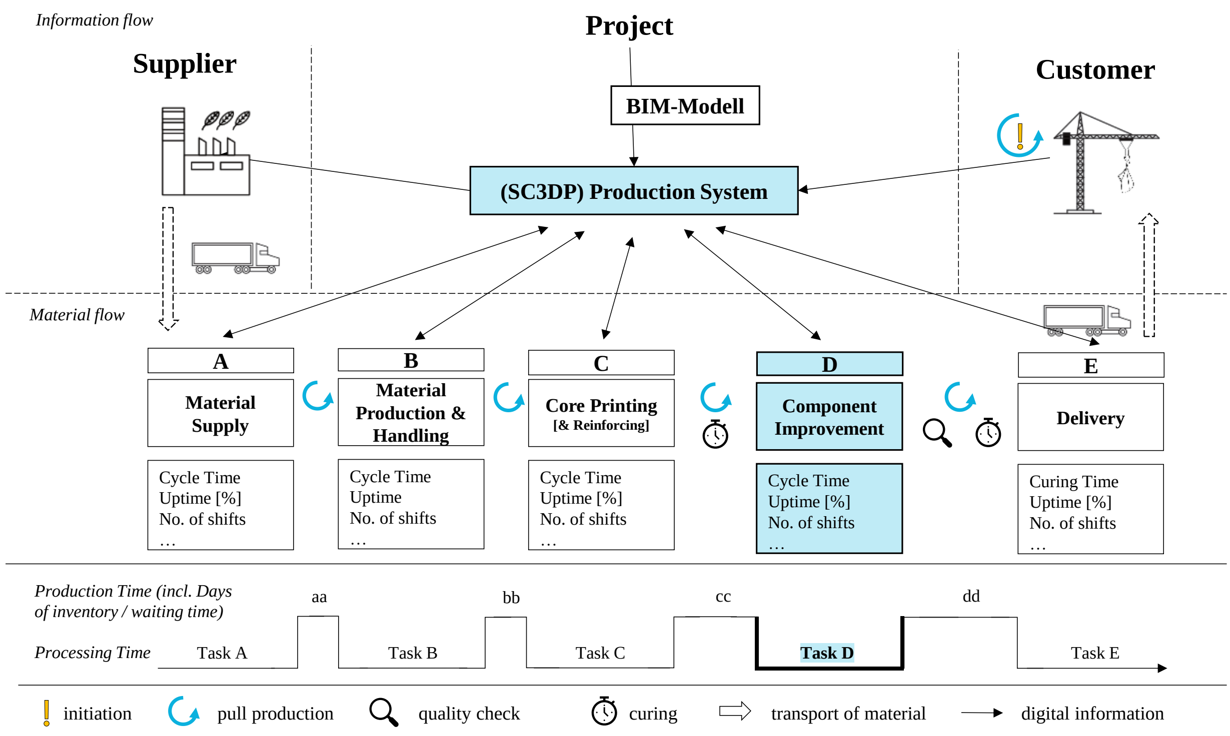

Figure 3: Lean-based Production Approach based on a value stream mapping

4.2 Bi-directional workflows for Component Improvement

Even in the field of digital fabrication, the possibilities of process-controlled component improvement are still limited and often depends on the skills of experienced workers and is labour-intensive [19]. To ensure the continuous quality control of surfaces as well as of the deposition process during the fabrication process and material damages during post-processing, the entire process must be monitored and validated. This can be done using a bidirectional workflow [20].

During the printing of the core structure in the SC3DP process, the required dimensions and tolerances must be observed and the previously shotcreted concrete has to be post-processed within the early phase of the curing concrete [21]. A delay can lead to defects such as cracking or other deficiencies in structural integrity. If the aging process is too advanced, it can lead to the damage of the formation and subtraction tools used or even to the failure of the fabrication system.

To create a hybrid manufacturing workflow for the shotcrete 3D printing process, a bidirectional workflow must be implemented. Feedback and quality inspections of the produced component must be established between each task of the process (see Figure 4).

In this workflow, a fabrication model is created from the as-planned design model, which includes the path planning along the fabrication parameters. After the transition to fabrication and the actual execution of the process, the process is validated by a data acquisition and a subsequent analysis. This can lead to a task iteration in the production process. Depending on the measured geometry of the actual produced component and previously produced components, the process parameters can be adjusted after each validation step. For example, material must only be applied where insufficient material deposition has occurred. These adjustments can be executed locally to minimize the production time of the actual component.

In order to control the various tasks of the manufacturing process, quality control must take place. This raises the question which requirements of the produced component are important and should be measured. Robot-assisted additive manufacturing of prefabricated building components with complex geometry involves more than visible large-area surfaces. Should the objects be joined, the contact surfaces may complex geometries for dry joints. The following chapter addresses some important aspects in this context.

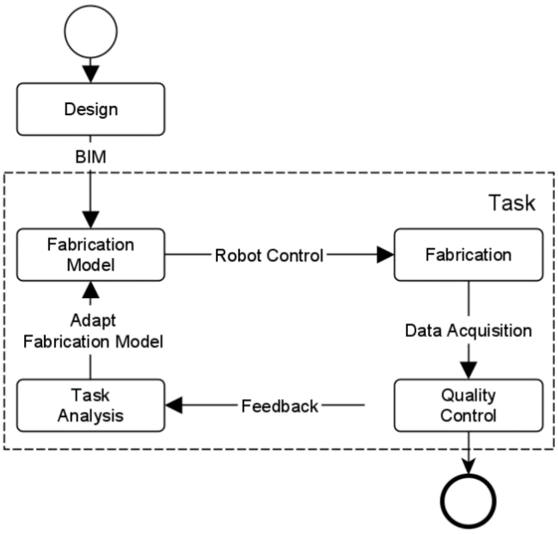

Figure 4: Bi-directional workflow for component improvement

4.3 Quality Check

To step forward towards the demands of industry 4.0 and meet the aspects of Lean-based production, as stated here as "value", not only the printed specimen's geometry must be checked, but also the existence of deformation on its surface.

Through the printing process, we have two main stages of the printed object. In the early printing process stage, especially in the core structure, the object is still in the forming process. In this step data capturing and processing speed are the major factors. However, in the surface finishing phase, the printed object reaches its final shape and develops to its digital twin. Therefore, at this stage, the accuracy of the process has to be treated with caution and be defined properly [22]. Accordingly, the need for having an integrated quality loop for every step is required.

An overview of different geometric aspects that could be controlled through the quality assessment process was given by [23]. The dimensions of the object and its tolerances are also two crucial parameters whose deviations from the as-designed model must be checked. This quality control guarantees a straightforward construction process and ensures that the original vision of the designer comes to light.

The integrated loop of QC in AMC adds another degree of freedom and establishes a bridge between construction and design. As an illustration, in the case of a printed specimen with a deviation from its digital twin, the modification needed for the deviation correction can be performed either on the printed object directly or on the designed model if the deviations are still in the acceptable range regarding the structural design.

5 Conclusion and Outlook

Bi-directional information flow provides the framework for the integration of additive manufacturing in construction and remains a necessary requirement for our Lean-based production approach. In addition, this a production approach can only get intelligent and truly efficient when it is actually based on building parameters (e. g. printing rate, layer thickness or curing time) as wells as on as-built geometry (by real-time measurement). Therefore, digital tools are required for a continuous and uninterrupted quality control throughout the entire construction process. Sensor feedback, data collection and interpretation play key roles here. Unforeseen issues during fabrication and construction that lead to deviations (as-built) from the design (as-planned) can be corrected instantly, the project's goals or the defined value can be fulfilled more efficiently compared to the current situation.

Applying LP principles and methods is playing a key role here. A holistic process understanding ensures that not only a multitude of relevant building parameters can be integrated right at the beginning (ex ante) of the design phase (e. g. structural requirements, fabrication con-straints, logistic restrictions, etc.), but also allows data to be collected after design completion (ex post) and during the fabrication and the assembly process on site. Those can be subsequently fed back into a centralized BIM model. Therefore, a database of AM production processes and parameters is of major importance. It would allow it to choose the best productions properties for a specific project/ production step. To analyse patterns or correlations in complex data sets, artificial intelligence such as machine learning can create a fully automated production. Hereby, it would be possible to identify trends and modify deviations between the production steps and various building parameters. This would finally lead to a new and truly "intelligent" production system merging current trends of lean (production) and construction.

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