Virtual construction with digital twins – The key for leanly planned complex construction systems

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Abstract

Lean construction planning is based on continuous improvement of processes. To this end, in current practice weekly look ahead meetings are planned among all contractors working on a construction project. During these meetings, the construction work and productivity of past weeks are discussed and the work for the upcoming week is planned, sequencing construction activities based on past experiences. While often successful in aligning work flows, current practice, by large, lacks the means to understand past construction work based on empirical productivity data collected from construction sites. Digital twins of construction projects that represent not only the current status on a construction site, but that also provide a digital representation of past construction work through construction simulations that are calibrated with past data, can provide the required empirical information. On the large European Ashvin project, we set out to develop the required digital twin platform and applications to provide such digital twins. This paper describes the envisioned lean construction approach to be developed during the project. Additionally, the paper will provide a number of reflection on how digital supported construction planning can further reduce waste by streamlining resources required for planning activities and by empowering the construction workforce.

Virtuelle Bauplanung mit digitalen Zwillingen - Der Schlüssel für Lean geplante komplexe Baubetriebssysteme

Zusammenfassung

Lean Construction fokussiert auf die kontinuierliche Verbesserung des Bauprozesses während eines Projektes. Dazu werden in der heutigen Praxis meist wöchentliche Planungsbesprechungen organisiert die alle Parteien die zusammen ein Projekt verwirklichen zusammenbringen. Während diesen Besprechungen, wird der Baufortschritt und – verlauf der vorherigen Woche analysiert und die Arbeit der nächsten Woche geplant. Was in der heutigen Praxis noch fehlt sind Möglichkeiten die Arbeit der vorherigen Wochen auf Basis von verlässlichen Daten zu analysieren. Digitale

Zwillinge der Baustelle, die nicht nur den gegenwärtigen Stand der Baustelle abbilden, aber auch mit historischen Baudaten kalibriert sind, und dadurch zukünftige Bauprozesse simulieren können, würden diese benötigten empirischen Daten liefern. Das europäischen Projekt Ashvin hat das Ziel eine Plattform für die Bereitstellung von digitalen Zwillingen für Baustellen zu entwickeln und spezifische Applikationen zur Unterstützung der Bauleitung die Daten des digitalen Zwillings verwenden zu entwickeln. Dieser Beitrag beschreibt die Ziele des Ashvin Projektes in Relation zur Unterstützung von Lean Construction und reflektiert über mögliche Zukunftschancen die der Einsatz von digitale Zwillinge von Baustellen auf Baustellen ermöglichen könnten.

Introduction

Lean Construction focuses on creating a reliable and predictable workflow on a construction site. Reliability and predictability is achieved through aligning the entire supply chain of a construction project to maximize value. To this end, in current practice the Last Planner System© is employed that “is based on a Should-Can-Will-Do system of project planning” [1]. the system suggests to create detailed weekly construction plans in a concerted team effort with all contractors working on a project. The approach is based on keeping track of the productivity of past activities and adjust the workflow of future activities accordingly [1]. The expectation is that these planning activities allow to align the work tasks of all contractors and, in turn, avoid conflicts between the different contractors working together on a construction site [2].

One inherent problem of the current process is that the weekly coordination meetings are supported little by empirical progress information collected objectively from the construction site. Discussions on how to improve construction sequences rather rely on the subjective experiences of the different participants in the meeting. Moreover, means to support the discussion about possible future process improvements through construction process simulations and visualizations cannot be meaningfully employed. It is therefore, not surprising that meetings often are hampered by the lack of accurate information about past productivity and often turn into politically infused discussions about the responsibilities of different contractors. While the Last Planner System© presents a large step forward towards achieving reliable and conflict free construction, the process is also still far from ideal.

The technological basis for supporting the Last Planner System© with high quality empirical data of construction projects can be provided by digital construction twins. Digital construction twins promise to provide accurate information about past productivity, current site conditions together with possibilities to accurately visualize and simulate current and possible future construction processes. The large European Union project Ashvin [3] set out in October 2020 to provide the technical foundations for such digital construction twins together with a set of proposed standards to support digital twin based construction planning. In this paper, I will introduce the envisioned lean construction planning work flow enabled by digital construction twins that we envision in Ashvin. Based on this introduction, I will provide a number of reflections of how a digital twin enabled workflow can further pave the way to realize two of the underlying philosophies of lean management. For one, current Last Planner System© based approaches are very resource intensive in terms of planning activities. In the sense if lean management planning can be seen as a wasteful activity, and should therefore reduced. Of course without, minimizing the final product quality that can be offered to the client. Additionally, one main pillar of the lean philosophy is the empowerment of the workers on the production floor. Therefore, I also will discuss how a digital twin supported lean construction process can bring the industry a step further towards truly empowering construction workers.

The paper is structured as follows: In the next section, I will briefly summarize the current state of the art in lean planning with a focus on the Last Planner System©. Afterwards, I will introduce the on Ashvin envisioned digital twin supported process. Before concluding, I will then discuss possible implications in terms of further improving lean management in the construction industry.

Lean Construction

Lean management is based on the idea to reduce waste within the production process. Anything that does not directly provide direct value to a customer should be managed out of the process with a target on eight specific types of waste: transport, inventory management, material movement and motion, waiting of staff or idle resources, overproduction, over-processing, and defects [4]. To identify waste in each of the categories, carefully designed improvement processes need to be implemented that are based on plan-do-study-act (PDSA) cycles [5].

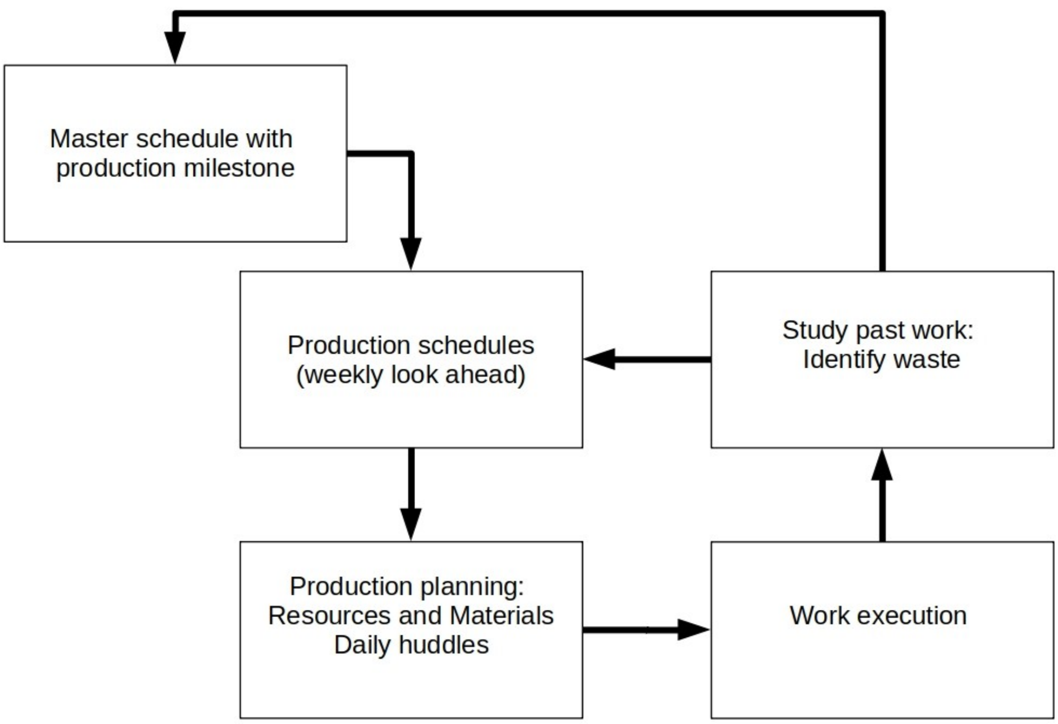

Figure 1: Lean construction management according to Fischer et al. [5]

Based on lean management thinking, Fischer et al. [5] suggest a lean construction management process as depicted in Figure 1. At the outset of planning a construction project, a project team should start developing an initial Master schedule that includes the main production milestones. The purpose of this schedule is it to sketch the main steps required for delivering a construction project for the purpose of understanding high-level construction and financing needs. Based on this high-level schedule, detailed production schedules should be developed by the construction team, ideally planning only the next week of work (weekly look ahead schedules). These weekly look ahead schedules can then be used by the different contractors working together on a project for detailed production planning in terms of resources and materials. More fine grained coordination between the different contractors might be required in the form of daily huddles to understand work tasks planned for each specific day. Construction teams can then conduct daily construction work that is well coordinated between the different parties. In a final step of the suggested lean construction management process, Fischer et al. [5] then suggest to study past work (closing the PDSA cycle), identifying sources of waste within the performed past activities and accordingly updating the master schedule, but also informing the development of the next production schedule.

A suitable tool to support above describe lean construction processes that has been widely used within industry is the Last Planner System© [1,2]. The Last Planner System© is a planning process based on a pull philosophy, during which all disciplines responsible for delivering a construction project work together on developing production schedules. The process starts with all parties brainstorming the construction tasks that need to be executed within the next planning horizon – usually a week. Based on the identified activities a sequence of how this process can be physically executed in the field without causing conflicts between the disciplines is then developed. The pull planning process usually yields a work flow for the work of all disciplines with a focus on sequences that repeat across different time frames, such as the sequences required to construct and built out the different levels of a high-rise building, or the sequences required to provide a linear infrastructure project, such as a road. Following the above suggested continuous improvement process, pull planning meetings are organized at regular intervals to update sequences based on lessons learned [6]. In current practice, planners support this process usually with the existing 2D drawings of the construction site, which they often annotate and mark-up, to understand which construction tasks need to be conducted. The planners then use post-it notes to plan construction sequences together (Figure 2).

The above describe process around the Last Planner System© is quickly becoming industry best practice and studies have shown that it helps to support construction projects to identify and remove waste from their production processes [1,2]. At the same time, in current practice the process is still very much based upon the subjective experiences of the participants in the meetings and the process of studying past work is supported little by objective productivity data collected about past construction. At best, careful efforts have been made to support the process with 3D visualizations of the envisioned building design and construction process visualizations of past and planned future construction sequences [1,7].

The missing possibilities of supporting these planning meetings with accurate information of existing site conditions and past production data, leads to a number of problems in current practice. For one the success of the meetings studying past work and developing improved look ahead plans is highly dependent on the participants within the Last Planner System© meetings. Often meetings fail to identify important sources of waste, because important experts are not present in meetings or because meeting participants are not interested in disclosing problems within their discipline due to political reasons. Even if all participants are discussing in good faith, oftentimes, discussions are detached from the actual work on the construction site. The lack of suitable information sources also often makes the meetings unproductive so that there is seldom time to really discuss and evaluate different alternatives for eliminating waste.

Figure 2: Example of a pull planning sequence developed in a last planner meeting using post-it notes [7].

To overcome, the above problems, accurate digital representations of existing and past construction activities could provide the required information to significantly improve the possibilities to reduce waste during lean construction activities. In the next section, I describe the vision of the Ashvin project of how to provide this support.

Digital Twin for Construction

Figure 3 provides an overview of the envisioned digital twin supported lean construction management process. This vision focuses on the steps of studying past work and developing the weekly look ahead schedules of the overall lean construction management workflow. To this end, four constitutive steps are suggested that should be executed within the regular Last Planner meetings: The review of the quality of past work, the observation of the past construction workflow, the simulation of possible future production workflows under consideration of various possible scenarios, and the key performance indicator (KPI) based selection of an optimal future production schedule. The following sub-sections will describe each of these steps in detail together with how digital construction twin data and applications operating on these data can be used to discuss the Last Planner meetings.

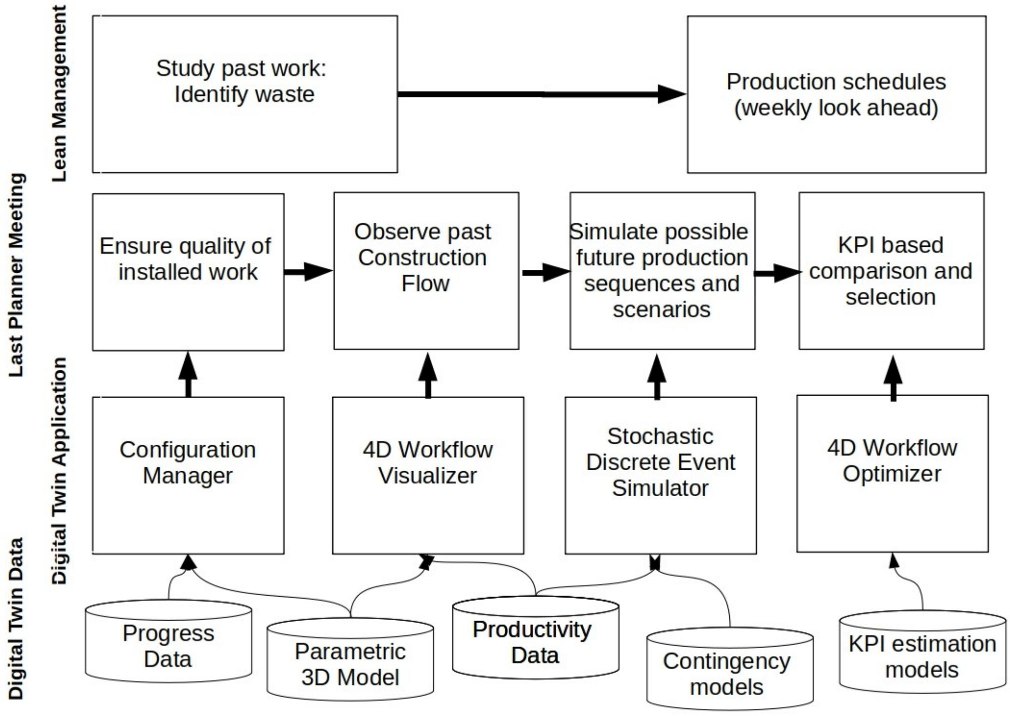

Figure 3: Envisioned digital construction twin supported lean management

Quality review of past work

At the beginning of each review cycle, a project team should ensure that the work that has been put in place in the last planning cycle reflects the required quality of the client. In systems engineering, this process of establishing and maintaining the consistency with the client's requirements is called configuration management. A digital representation of the construction project that a digital construction twin allows for can help the configuration management process as it would allow planners to clearly understand what work has been put in place in the last period. Additionally, the digital representation could also track the quality of the work based on manual and automated inspection processes. Important information that needs to be tracked are whether required tolerances are maintained, which construction products have been installed, and what materials have been used. The digital twin could also maintain a history of all conducted material quality tests. Another important part of this step is to review possible changes that have been implemented be it on client request or for any other reason.

In this first step, the above outlined information allows the planners than to understand whether the past work cycle delivered the required quality, or whether it under- or over-performed. Such an initial understanding of the quality of construction work is essential for understanding the appropriateness of the previous planned production schedule in the first place. Possible influences of certain production schedule steps on the quality of the work can be analyzed and reviewed.

Analysis of past construction flow

After understanding whether the past production schedule was able to deliver the planned work within the respective quality, the conducted work process can be analyzed in detail. To support this, digital information about measured productivity of the work of the different parties is helpful. Additionally, a digital construction twin would need to provide information on which task had been conducted at which location on the construction site. Again this information could be collected manually through time keeping and location tracking activities. However, information could also be automatically collected by equipping construction equipment and workers with appropriate sensor systems, such as GPS sensors or acceleration measurement devices [8]. Additionally, image recognition algorithms could be used to automatically extract relevant information from video recordings and time lapse photos [9, 10].

A suitable digital twin representation to support this step, combines all respective information to provide an accurate 4D model of the past construction progress. Such 4D models are able to visualize construction progress within two-dimensional or three-dimensional views. Previous research has already shown how such 4D models can provide meaningful support for Last Planner meetings [1, 2, 7], the availability of a suitable digital construction twin would significantly reduce the amount of work required to generate such 4D models.

Simulation of possible future production scenarios

Once the quality and the flow of the past construction has been analyzed, planners can jointly develop possible new production plans for the next work period. If a suitable digital construction twin is at hand, planners could be supported with analyzing possible new work sequences using past stochastic production data combined with discrete event construction process simulations [11, 12]. These simulation allow planners to better understand the expected timing of activities which is crucial to develop sound and adjusted workflows. The simulations also allow for the analysis of different possible sequences.

Moreover, if sufficient historical productivity data is available, planners could even develop different scenarios that use productivity predictions that are contingent on different external factors. The effects of, for example, different weather conditions on productivity of outside construction tasks, variances in soil characteristics on excavation tasks, or the effects of different specialized equipment or workforce skills, on the flow of different construction sequences can be analyzed. A selection of a certain amount of different production plans could be developed and used for the subsequent selection of an optimal production schedule in the last step of the digital construction twin supported planning process.

Selection of optimal production schedule

At the end, the goal of the above envisioned lean management process needs to be the selection of an optimal production schedule for the next planning period. To this end, possibilities need to be provided that allow planners to weigh the advantages and disadvantages of the different developed future production sequences and scenarios against each other. To allow for an objective comparison, a set of clear key performance indicators (KPIs) should be chosen that can be automatically calculated for each of the different alternative sequences and scenarios.

On the Ashvin project, we already developed a first set of KPIs along three main performance categories for construction projects: reduction of costs, resource allocation efficiency, and safety. For reduction of cost, possible KPIs could be a reduction of heavy equipment required for a respective production schedule, reduction of scrap materials and other physical waste, or reduction of rework – all of which could be continuously measured and estimated based on historical project data. For efficient resource allocation, KPIs could be the percent of non-productive work time, idle time for heavy construction equipment, or the reduction of greenhouse gas emissions caused by construction work. For safety, KPIs could be reduction of non-fatal accidents or near missed accidents. Again, the calculation of all of these key performance indicators might require a good basis of collected historical information that are part of well developed digital construction twins.

Discussion

"… crews would install their work only once at the right time and in the right sequence to make good on the promise their foremen made in the weekly production planning meeting. Hand-offs between trades would be without surprises and as promised. Crew members would have the right skills and equipment to do their job safely. Crews would be working from documents, which are clear, accurate, and correct. There would be no outstanding design questions or changes being considered when the crew began work in a particular area. The work area would be clean and unobstructed. The crew would be aware of hazards and would have taken appropriate measures to protect themselves and anyone else who might be in harm's way. The crew would understand the quality expectations and would have developed a work plan to produce nothing less than what was expected. The right material would be ready and close at hand without obstructing other workers. The crew would have been given adequate time to do their work correctly. The crew leaders would share problems as soon as they emerged and announce completion of their work as soon as they knew when that would likely be." …. from Fischer et al. [5]

The above depicted vision for a construction site still seems to be far away from current practice. However, I believe that with the above described framework for digital construction twin supported lean management, it will be possible in the foreseeable future to move closer to Fischer et al.'s [5] vision. Technically it will be already possible to provide the required supporting technology for the above sketched process. In fact, researchers have developed and demonstrated most of the required innovations albeit at a relatively low technology readiness level. The next step, to move to the vision depicted here will be to assemble the different recent innovations and research results into a integrated digital construction twin system. Additionally, the required applications that make use of the digital twin data as sketched above need to be provided. Goals that the Ashvin project has set for itself and will strive to realize in the coming years.

Once available and implemented, above an beyond supporting last planner activities, the provision of digital construction twins have the additional potential to help reaching some additional lean management principles that have so far not been widely considered within the construction industry. For one, in a strict lean philosophical sense design, estimating, planning and project management are only supporting activities that do not produce value [5]. All these activities must be considered, therefore, as waste and should be reduced as much as possible. Most lean construction approaches currently, however, rather seem to suggest invreasing planning and project management activities instead of reducing them compared with traditional practice. Even the required contractor meetings in the Last Planner System© require pulling together quite a significant amount of expensive planning resources. Considering the above mentioned process, future developments could focus on more and more automating the process. As data from past construction projects and processes are collected and become readily available, external contingency effects, such as local site conditions, weather, or labor skills can be modeled statistically. At the same time, databases of standard sequences for production schedules can be established [13]. Based on such past information, computational methods can be devised that can automatically create a vast amount of production plans. Computational optimization algorithms can then be used to identify optimal production plans without much requirements for the interventions and discussion of planners in the process.

At the same time, current lean construction approaches are heavily management led, with very few explicit feedback loops involving construction workers. At best, some projects involved foreman within daily huddles. One important ingredient for lean management however is that pull based management approaches are established that are driven from the bottom of the production supply chain. Pull processes and requests should be ideally initiated from the persons that directly provide value to the customer, which on construction sites are the workers that put work in place. Best practice lean examples from the manufacturing industry [4] have shown that the inclusion and empowerment of workers on the shop floor is possible and that state-of-the-art digital twin solutions can support such approaches. For example, suitable digital construction twins could include and support inventory management that would allow workers to directly ensure that the right amount of material is available at the right time. Reliable digital twin applications also allow workers to quickly understand deviations from planned procedures. Possibilities to directly and flexibly change workflows or task assignments might be possible in the future without the requirement to involve upper management instances. The current Last Planner based approaches could change towards First Planner philosophies in which planners only provide an initial high level Master plan for a construction project, while all work planning activities can be flexibly organized directly by skilled construction workers on site that are supported by digital construction twin technology that provides all required information, can suggest flexible work sequences and task assignments, and provide a continuous configuration, as well as quality management.

Of course, to reach the above vision suitable digital construction twin technology needs to be developed and demonstrated in practical settings. Additional, industry standards and widely applicable processes need to be developed that can be readily applied to make use of digital construction twin information. This will require concerted research and development efforts to overcome a number of still prevailing problems and bottlenecks. These efforts need to involve industry, or ideally be driven by industry, as it will be important to understand the granularity and type of information that is required to be represented by the digital twins. The involvement of practitioners will also be important to design and develop applications that leverage digital twin data so that they become useful in construction practice. One major problem that still needs to be addressed is how to collect and store the required digital twin data without infringing on the individual privacy rights of construction workers.

Conclusion

This paper introduced a framework for supporting lean construction practice with digital construction twins. Additionally, the paper provided some initial reflections on future possibilities to further improve lean management processes using digital construction twins in the future. The introduced framework mainly focuses on supporting the common Last Planner practice in construction, enabling last planners to review past construction activities and to develop better production plans for future planning cycles. Within the reflection, possibilities to reduce planning activities are elaborated on that could provide a significant step change in terms of reducing waste within delivering construction projects that is caused by the currently required intensive management involvement. The paper closes with a call to action for future research into digital twin technologies that need to be industry driven.

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