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LEAN PRODUCTION CONTROLLING AND TRACKING USING DIGITAL METHODS

Jakob von Heyl[1] and Jochen Teizer[2]

Abstract: Lean construction projects are understood as temporary production systems that eliminate waste, allow collaboration and optimize structures of the value added chain. Remaining crucial challenges in construction are the coordination of the involved trades and the tracking of construction progress. Current research in Lean Construction Management (LCM) targets automated digital methods that support work package planning and make inferences about states of progress. The scope of the presented work focuses on closing the feedback loop of lean construction planning, progress tracking, and status control by using 4D information from Building Information Modeling (BIM) as well as Internet-of-Things (IoT) technology for reporting actual progress.

Keywords: Production Planning and Control, Last Planner System, Takt Planning and Takt Control, Information Management, Building Information Modeling, Information and Communication Technologies, Automated Progress Tracking.

1 INTRODUCTION

Lean principles are based on several preceding economy of scale production approaches, originating from the ship building, aviation, and car manufacturing industries. Two prominent examples are Taylorism and Fordism. After the Second World War, Toyota adapted the ideas of Taylorism, Fordism and several other approaches, such as Total Quality Management (TQM), to a flexible production system with several products and variable batch sizes. A set of different principles, methods, and tools that reduce buffers, set-times and waste were consolidated in the Toyota Production System (TPS) (Womack et al. 1990). The term lean was coined by Krafcik in 1988, who described the advances in productivity of the Japanese automotive industry in comparison with western manufacturers (Krafcik 1988). His research was continued by Womack, Jones and Roos at the MIT in Boston, who identified a large productivity gap between Japanese and western car manufacturers and suppliers (Womack et al. 1990). Many attempts by western manufacturers to copy specific TPS-tools failed. Therefore the main ideas were abstracted and bundled in the Lean Management Theory (Drew et al. 2004). Specific solutions can be derived from that theory for any industry or company.

The adaption of Lean Management to the construction industry was first examined by Koskela in 1992. He developed the TVF-Theory, saying that construction can be described with the transformation of resources and the creation of Value and Flow of materials and people. (Koskela 1992). Ever since then, several lean production control methods have been developed for the construction sector.

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2 LEAN PRODUCTION PLANNING AND CONTROL METHODS

Two prominent Production Control Methods (LPS and TPTC) are explored:

2.1.1 Last Planner System (LPS)

The Last Planner is the project participant accountable for the execution and control of operative tasks. The Last Planner System (LPS) is a method to manage the tasks in the design or construction phase of a project. The main idea is to shield near-term work via a network of commitments in order to improve reliability and workflow, resulting in an improved adherence to schedules and productivity (Ballard and Howell 1994). LPS leads to a decentralization of management tasks and promotes cooperative work. Working areas, tasks, and schedules are planned by a team consisting of the affected project participants. This improves commitment and solution orientated teamwork. LPS consists of four phases aimed to develop more detailed plans as the project moves on (Koskela et al. 2010) (see Figure 1).

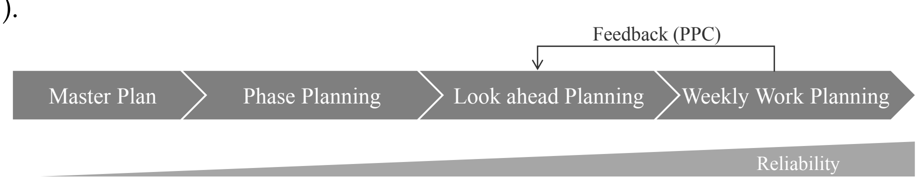

Figure 1: Phases of LPS

LPS is a method to successively identify, prepare and execute required working steps. After a general set-up, work is getting pulled and made ready for execution while becoming more precise and detailed. The supply chain is getting permanently adjusted. According to Ballard and Howell three categories of constraints have to be considered (Ballard and Howell 2003):

1. *Directives:* Information required for execution (e.g., design documents)
2. *Prerequisite work:* Work needed to be completed before the start of specific tasks.
3. *Resources:* Labour, equipment and space required for the execution.

In comparison with traditional Methods, like the Critical Path Method (CPM), LPS focuses on reduced variability. This indirectly leads to improved productivity rates, reduced durations, and resource consumption. A disadvantage of LPS is the missing reflection of the current status of the construction site on higher planning levels (Koskela et al. 2010).

Furthermore, LPS is a bottom-up management approach based on cooperative work packaging and commitments. Activities are constantly getting prepared for execution by the responsible project participants. In order to prepare work for execution, related constraints have to be identified and removed. Therefore LPS relies heavily on correct information to assess work progress and the use of resources.

2.1.2 Takt Planning and Takt Control (TPTC)

“Takt” is a German word that can be translated as pulse, cycle time or work cycle. It is also referred to rhythm or cadence, as it describes something is done regularly and on time. Takt-time is used to schedule production and supply times (Frandson et al. 2013). The first known use of Takt-times dates back to the 16th century, when merchant ships and warships were produced in Venice using a Takt. With the industrial revolution Takt was becoming a part of many production approaches, such as Fordism or Toyota Production System (TPS) (Haghsheno et al. 2016).

Takt is mostly used in repetitive construction processes. This criterion is particularly met by linear infrastructure projects, e.g. the construction of bridges, tunnels, roads or railways (Haghsheno et al. 2016). The structure and manufacturing processes determine the size of the working area, the required effort and working steps as well as the productivity rates. These are the input variables for the calculation of the Takt-time in order to achieve a consistent production speed. Prefabricated elements, which are often used in infrastructure projects (e.g., bridge elements or tunnel lining elements), facilitate the determination of suitable segments and the calculation of working times.

The use of Takt in the construction industry is nowadays strongly intertwined with the method Takt Planning and Takt Control (TPTC), which has been developed in Germany in the middle of the last decade. TPTC has been applied in numerous construction projects since then (Haghsheno et al. 2016). The preparation of a Takt-based production is done in two main steps, the process analysis and the Takt-planning. Each of the two steps can be further differentiated in three steps (Frandson et al. 2013). The outcome is a production plan including time and space. The compliance with the production plan is checked constantly during the next step, known as Takt Control (see Figure 2). The working packages are highly interdependent. Therefore a permanent control and update of the production plan is required in order to deal with potential changes and disruptions. To ensure production stability, current developments are monitored and necessary adjustments are made immediately in regular meetings (Haghsheno et al. 2016, Kenley and Seppänen 2010).

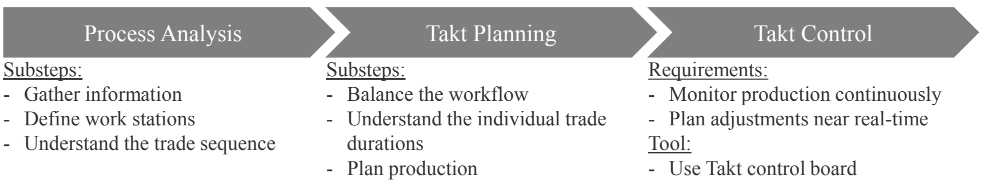

Figure 2: Procedure of Takt Planning and Takt Control

Takt-planning is top-down approach and requires reliable plans and a deep understanding of the structure, the construction process, as well as the supply chain. There is a high demand for correct and up-to-date information in order to constantly adjust the production plan. When these requirements are met Takt-planning becomes a powerful method to increase the stability and reliability of the production. Disadvantages arise in reacting to unexpected events as the method lacks flexibility. The higher the number of alternations or modifications, the less it is suitable.

2.1.3 Comparison

LPS and TPTC work differently but are both aiming to achieve a continuous flow and improve project understanding due to the visualization of the tasks, processes and dependencies. Both methodologies have in common that they require a continuous monitoring of the production and a functioning information and communication management system. The differences are that TPTC is a rather rigid top-down method requiring a stable supply chain and little variability. LPS is a more agile bottom-up approach focusing on mutual agreement between the project participants. Main differences of the two approaches are depicted in Table 1.

Table 1: Comparison of LPS and TPTC

Criteria	LPS	TPTC
Management Direction	Bottom-up	Top-down
Collaboration	High	Low – Medium
Spatial link	Low – Medium	High
System-Stability	High	High, when little variability
System-Flexibility	High	Low

Pending on the project conditions, one method can be more suitable than the other. Recent research suggests that LPS and TPTC can be implemented together, using Takt Planning to optimize the allocation of materials and resources to specific work site locations and using LPS for production controlling (Emdanat et al. 2016, Frandson et al. 2014). In addition features of other Production Planning and Control (PPC) methods, like LBMS, CCPM, and EVA, can be integrated:

- LBMS provides spatial elements and forecasting capabilities (Dave et al. 2016).
- Critical Chain Project Management (CCPM) enables a systematic removal of constraints (Koskela et al. 2010).
- Earned Value Analysis (EVA) offers a general controlling approach over all phases and integrates data for forecasting functions (Turkan et al. 2013).

The authors propose that a set of different methodologies and technologies should be combined to leverage the known advantages for each project depending on the goals and character. The suitability and possible combinations is an important research topic of the future. The combined use of different methodologies emphasizes the need for a functioning information management to ensure a correct exchange of information.

2.2 Information Management

Information management is key to the successful implementation of production controlling methods. A constant and reliable flow of information to assess work progress, constraints and productivity is required. The main data types are: *planned data*, *actual data* and *forecast data* (Berner et al. 2015). The data is collected on a regular basis. The loop times for feedback (e.g., weekly) are chosen in regard to the project phase or method applied (see Figure 3).

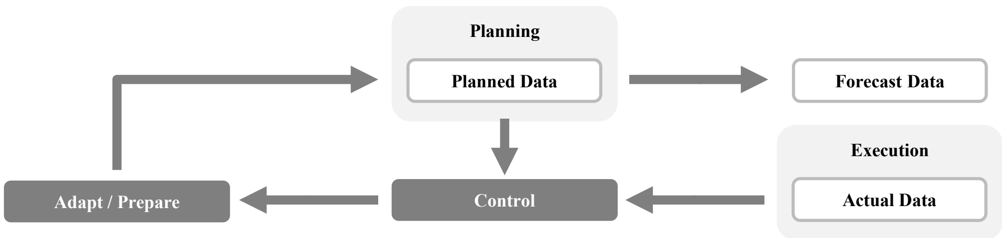

Figure 3: Control loop

2.2.1 Planned Data

The design documents or task assignments contain the planned data. The planned data is more accurate the closer it gets to execution. In early project phases planned data is being specified on top-level containing general information about working packages, budget and schedules, e.g. milestones. The information is consolidated in master plans. Over the course of the project more information is available, thus planned data becomes more detailed and accurate (e.g., weekly work plan or Takt plan).

2.2.2 Actual Data

Actual data is collected during execution. An improved production management with fast reaction times requires reduced cycle times for the collection of actual data (Emdanat et al. 2016). Actual data is needed to assess the performance and contains information about quantities, labour hours, costs or execution times. It provides feedback to identify necessary adaptations and improves the preparation of working order. Key Performance Indicators (KPIs) facilitate the identification of shortcomings. They are calculated using actual data. Each method is using individual KPIs (e.g., Percent of Scheduled Assignments (PAP) or Percent Planned Complete (PPC) as part of LPS). While the collection of actual data is a prerequisite for the calculation of the different KPIs, the initial emphasis of this research is on tracking the completion of tasks.

2.2.3 Forecast Data

The task of forecasting is usually assigned to the most experienced construction managers, who often go with their gut feeling instead of using systematic forecasting methodologies. This might be satisfying in small projects, but projects with higher complexity require a more profound approach. Plausible forecasts can be calculated using up-to-date planned data and actual data, e.g. Estimate at Completion (EAC) using EVA (Turkan et al. 2013) or forecasts generated with LBMS (Dave et al. 2016).

2.3 Limitations

Studies show that there is a limited reflection of the current status of the construction site in the master or phase planning if LPS or TPTC are not sufficiently integrating suitable controlling and tracking functions from other methodologies. There is a need to compile and integrate tracking and forecasting information as feedback and input for fruitful look-ahead or Takt planning sessions (Dave et al. 2016). This is prerequisite for a successful identification, preparation and execution of single working steps.

The collection of actual data is a crucial step towards informed management systems and serves as a prerequisite for further successful production planning and controlling. Current progress on projects is often compiled manually which is very time consuming and prone to human error. It leads to overall lower product quality and decreases the chances for successful risk mitigation.

3 DIGITAL PROGRESS TRACKING

Construction research has been increasingly focusing on discovering synergies between the adoption of lean practices and information and sensing technologies (Navon 2007). The use of information and communication technologies (ICT) are in particular beneficial to lean practices when they improve the flow of construction processes by identifying non-value adding activities that can be eliminated. Other examples are cycle-times that can be shortened, rework, variation and errors that can be omitted (Sacks et al. 2010).

Lean management and the adaption of technology is not new to construction. Several practical field applications exist, for example, Radio Frequency Identification (RFID) for pipe spool tracking (Song et al. 2006), Global Navigation Satellite System (GNSS) for earth hauling operations (Pradhananga and Teizer 2013), and wireless Real-time Location Sensing (RTLS) for tracking repetitive travel patterns of workers (Cheng et al. 2013). As outlined by Sacks et al. (2010) and Cheng et al. (2010), much stronger ties between Lean, BIM, and tracking technology are needed. Formalization of work-in-progress based on point cloud sensing (Bosché et al. 2013) and vision (Han et al. 2015) approaches are emerging, but yet require large manual input and make it impractical.

While digital transformation remains an ongoing challenge in construction and in research, central data storage and planning with BIM can be considered state-of-the-art. The focus of the proposed concept (see Figure 3) is on tightening Lean and BIM methods by supplying actual data via automated tracking and reporting technology. These enable rather than reduce the capacity of construction personnel by making high fidelity information available that previously has neither been recorded nor analysed. The continuous and rapid availability of up-to-date field data contributes to facilitating higher task quality, quantity reporting, on-time project delivery, and safe value creation processes.

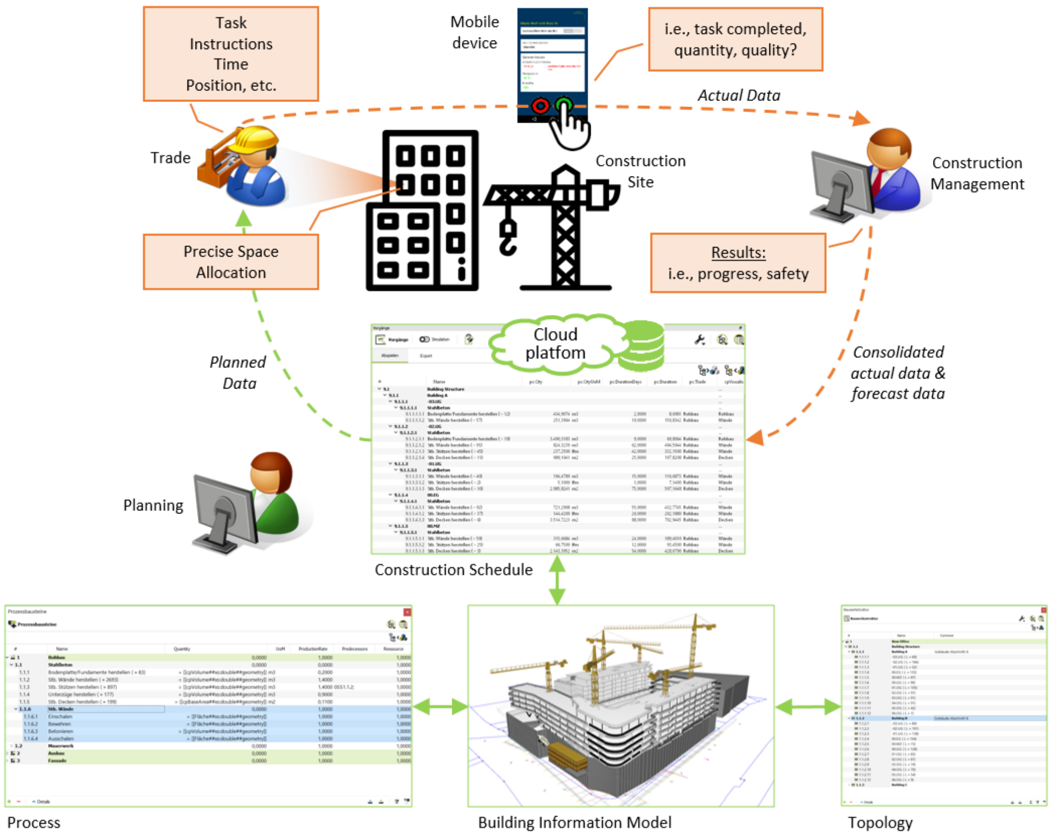

Figure 3: System detecting planned and as-is data, i.e. construction schedule (start, end), dependencies, quantities of tasks, and visualization.

4 Preliminary Results

The proposed approach uses nD-BIM for planning the topology (i.e., work station/location) of resource-loaded processes (i.e., name, dependencies, quantity, cost, required resources), and links geometric information to an automatically derived construction schedule (i.e., duration, quantity, trade). An Internet-of-Things (IoT) platform relying on wireless location tracking and reporting technology (e.g., Bluetooth Low Energy (BLE) sensors, mobile devices and a cloud database make the information of directives, prerequisite work, and resources available to authorized users.

To that extent, the authors enable the collection of relevant data with IoT-functional equipment, store the data in an IoT-platform and connect it to a BIM system to seamlessly integrate real-time data. In a use-case the authors tested the lightweight infrastructure solution for indoor tracking of personnel. A further test automated the process of time recording. Combining the traceability of the personnel's location and timestamp enabled the IoT/BIM-platform to collect and visualize actual performance data (desktop screenshot in Figure 4). More tests in realistic construction settings are planned.

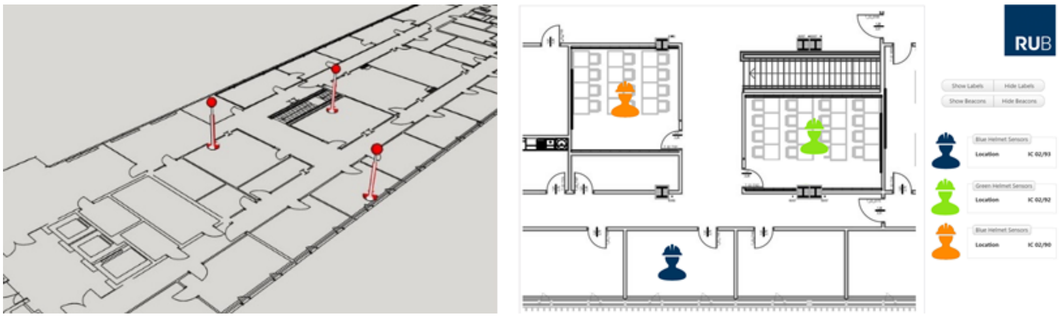

Figure 4: BLE-beacon positions in BIM (left) and real-time presence of workers (right)

5 CONCLUSION

Methods including Lean Construction Management (LCM) and BIM alongside with progress detection and tracking technology have the potential to assist construction personal in some of their challenging work tasks: (a) planning with reliable high fidelity actual information, and (b) detecting and tracking progress based on the presence of trades or on activity completion. A needs statement led to the proposed concept that integrates the three categories of constraints (directives, prerequisite work, and resources). Although preliminary experiments utilizing an IoT-platform show early, but promising results, more extensive testing in field realistic work environments is required to validate the selected approach.

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