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RESEARCH ARTICLE

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Development of a BIM-based production planning and control system for Lean Construction through advancement and integration of existing management techniques

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Abstract As part of general construction management, production planning and control is vital for successful project delivery. Numerous approaches supporting production planning and control exist in practice and research. However, the different approaches focus on distinct areas such as workflow stabilization or cost control, and no single system combines all the requirements of a holistic production management system. Varying production management systems can be explained by the unique characteristics of many construction projects. As an approach for the digital twinning in the construction industry, building information modeling (BIM) can help standardize production management through shifting the management system design toward the digital prototype. Previous scientific work has acknowledged this approach, thereby generating numerous concepts for using building information models within construction management approaches. However, BIM is often merely used as a parallel support rather than as an integral part of production management systems. To address this gap and in terms of research methodology, we follow a Design Science Research approach. Thus, we propose a new BIM-based production management system, which is characterized by a theoretical integration model for BIM and existing construction management techniques, and a methodology for applying these concepts in practice.

Keywords production management system design, Industry 4.0, Last Planner System, Kanban, earned value management

1 Introduction

This paper extends the work that was originally presented at the 27th Annual Conference of the International Group for Lean Construction (Schimanski et al., 2019). The discussions in this paper are primarily based on presentation feedback. In particular, the suggested integration of existing management techniques with the Last Planner® System (LPS), as a method from Lean Construction Management, is thoroughly explained and critically discussed. Thus, an extended conceptual model for integration, which is based on the findings of an integrative literature review (Schimanski et al., 2020), is formulated. In addition, the description of integration on data processing level with the approach of building information modeling (BIM) has also been extended.

This work aims to design a new Lean BIM-based production management system in construction. In contrast to stationary manufacturing, the construction industry (CI) often merely deals with temporary production systems owing to the inherent unique characteristics of most projects. Consequently, the manner of managing these production systems often varies from one project to another. Therefore, productivity in the CI is significantly lower than in stationary manufacturing (Pasetti Monizza et al., 2016). The adaptation of Industry 4.0 ideas is perceived as one of the keys to increasing productivity in construction (Dallasega et al., 2015; Maskuriy et al., 2019). As a method for digital representation of physical and functional characteristics of buildings and thus the

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provision of data, BIM can be considered a starting point for Industry 4.0 in construction. Industry 4.0 in stationary manufacturing aims to reach the optimum flexibility while maintaining productivity rates of the mass production era, and the CI intends to industrialize the factually existing one-of-a-kind production and thereby increase productivity (Pasetti Monizza et al., 2018).

However, a BIM-based approach for uniform production management systems could potentially overcome the limiting factors, such as fragmentation, temporary production facility, and one-of-a-kind product. Thus, the control of the project could be improved and standardized, and the execution planning could be simplified.

The systematic use of BIM models, which are rich in valuable information, could streamline the information exchange processes among stakeholders during execution. Shifting production management system design efforts toward the BIM model, particularly toward the digital prototype of the later building, can help to introduce standardized production management routines that are independent of any unique building or site characteristics. Hence, the proposed production management system provides for the integration with BIM data as an inherent information baseline.

To this end, the challenge of generating BIM data that are systematically available for the execution process must be addressed. The combined use of Lean Construction methods is a possibility for the standardization and systematic use of BIM models in construction execution (Sacks et al., 2010a). In fact, synergies that are attributed to BIM functionalities and Lean principles are described in numerous scientific publications (Sacks et al., 2010a; 2010b; Dave et al., 2013; Khan and Tzortzopoulos, 2014). In particular, the LPS is identified as the most suitable Lean method for construction execution processes to exploit these synergies (Sacks et al., 2010a). The LPS developed by Ballard (2000a) supports production planning and control by providing systematic routines to increase workflow reliability and process stability. The most important elements for achieving increased workflow reliability and process stability are collaboration, transparency, continuous improvement, and commitment from task leaders who are responsible to actually fulfil the work on site, namely, the Last Planners. However, Uusitalo et al. (2018) complain that the LPS does not offer indications for its application in BIM-based processes. In this study, we aim to address these limitations and create an information system based on the integration of BIM and LPS as the pillar of our proposed production management system.

Several attempts have already been performed to combine BIM and LPS in practical and scientific contexts. This paper briefly describes these attempts and discusses their limitations of solely constituting frameworks for co-application, rather than true integrations. Thus, we present an integration model on data processing level that describes how LPS process information is stored in the Industry Foundation Classes (IFC) file format as a non-proprietary data exchange format for BIM models and abstract it to a conceptual model based on the findings of an integrative review on BIM and LPS combinations (Schimanski et al., 2020). Moreover, we elaborate a methodology for its application based on agile method engineering strategies. We show that aspects from existing management techniques can enhance the proposed production management system and consequently integrate them in adapted form. These aspects cover ideas from Scrum, Kanban, and Earned Value Management (EVM).

For convenience of wording and as a symbol for the fusion of BIM and Lean, we name the proposed production management system as BeaM!.

2 Related work

Literature reveals that challenges on integrating BIM with LPS remain. For instance, Toledo et al. (2016) criticized the recent Lean and BIM research and documented that it is limited to theoretical synergy possibilities of both approaches and has slightly focused on the development of practically applicable methods and tools. Therefore, they proposed a Lean–BIM planning framework, where they included an Autodesk Revit® BIM model in the LPS process, and explained how it can be used most efficiently in the various LPS phases.

Guerriero et al. (2017) developed the Smart Construction Planner as a Lean IT-tool, which supports collaborative planning according to the LPS. Furthermore, they mapped the LPS steps to BIM 4D scheduling and argued that a framework for joint application should follow their research activities.

Gerber et al. (2010) investigated the co-application of selected BIM functionalities with certain Lean principles from Sacks et al. (2010a) through case studies. One of these case studies interprets BIM as a starting point for process and look-ahead planning, without consideration of the LPS methodology to its full extent. However, they believed that Lean and BIM approaches are inextricably linked, but further research should be conducted to support their hypothesis.

Bhatla and Leite (2012) also attempted to combine LPS and BIM in practice for evaluating the assumption that Lean and BIM are dependent of each other and most benefits can only be obtained when both approaches are used together. However, they solely implemented look-ahead and weekly work planning (WWP) of LPS that were included in regular BIM coordination meetings. In addition to mere partial LPS implementation, the make-ready activities were limited to clash-free ducts that were checked using BIM models.

Garrido et al. (2015) used an integration framework of BIM and LPS developed by Mendes Jr et al. (2014) in two case studies in Brazil. They concluded that BIM models support decision-making processes during LPS phases owing to their ability to provide the right information at the right time. However, these studies failed to use BIM and LPS in an integrated information system but in a detached manner wherein one system supports the other.

Lagos et al. (2017) also emphasized that the IT-supported use of LPS correlates positively with Percent Planned Complete (PPC) values. They perceived that the systematic make-ready process of tasks and progress monitoring can benefit from IT-support, particularly during the planning of the execution process. However, the authors argued that standardization in this sense can only be achieved through improved communication and a frame-giving knowledge management system (KMS). BIM can be interpreted as an approach for an effective KMS (Deshpande et al., 2014). Hasan and Akbas (2017) considered such a notion and claimed that BIM can improve and streamline look-ahead planning. Nonetheless, they observed significant challenges in structuring and preparing data for managing the execution process on site. To address this challenge, they propose a generic information management approach by aggregating the BIM data and other information required for look-ahead planning such as crews, equipment and basic workflows on an online platform. This platform is a prototype simulation platform that automatically generates a simulation model for construction processes for a given input. However, the collaboration aspect of the cooperative phase planning of the LPS is neglected, and the computer-assisted optimization of master schedules is given attention instead of establishing a production system according to Lean thinking.

In the field of BIM and Lean supporting IT systems, VisiLean, which is developed by Dave et al. (2011; 2013), should be mentioned. VisiLean is a cloud-based construction management tool that supports LPS principles and is paired with BIM. Tasks can be linked directly to BIM objects, and thus, the progress can be visualized via the model. However, quantities and other BIM information with regard to these tasks must be entered manually. The BIM model does not deliver them automatically. Furthermore, a "phase" within the system is solely interpreted as a far-reaching look-ahead window (e.g., 3 months). Nevertheless, the elements such as deep collaboration and hand-off discussions that characterize cooperative phase planning among the Last Planners are disregarded.

With regard to information systems, Sacks et al. (2010c) described a list of 6 fundamental requirements for an integral BIM-based Lean production management system for construction, which are related to visualization capabilities, support availability, the establishment of pull systems, workflow stability, and continuous improvement. These requirements have been implemented in the IT system KanBIM (Sacks et al., 2010b; 2010c), which is based on the hypothesis that IT systems can significantly enrich the LPS through enabling access to 3D building representations. We argue that as non-BIM approach, pure geometric 3D representations are insufficient for a complete production management system involving the three target variables, namely, quality, schedule, and costs. We consider that an effective production management system should exhibit accurate knowledge on the quantities of construction and the associated costs to follow the road toward industrialized construction processes.

Therefore, we propose that the point (7) — automatic and precise quantity-take off for process management — should be added to the list of requirements of Sacks et al. (2010c). To further complete this list, we also suggest to introduce point (8) — clear roles within the processes, which is considered and explained in Section 4 in this paper. We regarded these requirements and the described current absence of an integration of BIM with LPS to a joint information system as an opportunity to propose a concept for a new Lean BIM-based production management system in construction. This concept is introduced by presenting a theoretical integration model and supporting artifacts that are developed through a Design Science Research (DSR) approach.

3 Research strategy

This paper follows a combined research approach that is composed of a systematic literature review addressing the co-applications of BIM and LPS in previous studies that represent the pillars of our proposed production management system. This is followed by a DSR approach to develop new artifacts for system integration, thereby allowing for a joint application. DSR is considered a suitable approach to address construction management problems through developing and/or testing new solutions (Khan and Tzortzopoulos, 2018). As a robust research methodology, DSR is characterized by (1) finding a problem relevant to practice that also exhibits research potential, (2) obtaining knowledge on that topic, (3) proposing a knowledge-based solution for the problem, (4) showing that the solution works through demonstrating utility, (5) proving the connection to theory, and (6) evaluating the applicability under certain conditions (Kasanen et al., 1993). Mollasalehi et al. (2016) and Hamzeh et al. (2019) represent examples of the application of DSR as research method in construction management research.

Hence, a specific problem is initially presented, and the hypotheses for a possible solution to that problem are elaborated. In this case, the problem is the lack of standardized production management systems in construction. The true integration of BIM and LPS on data processing level, which goes beyond their parallel co-application, is suggested to solve this problem.

Subsequently, we create concrete artifacts in the development phase according to DSR, which includes the theoretical BIM–LPS integration model and a methodology for application in practice as part of the proposed new production management system. The requirement analysis for software implementation of the BeaM! system and the actual software development based on the requirements are not within the scope of this study and will be addressed in future publications. Similarly, the evaluation phase according to DSR is not tackled in this paper. Figure 1 illustrates the research strategy.

4 Developing artifacts according to DSR

The development of the two artifacts (methodology and integration model) according to the applied DSR strategy is presented in this section.

4.1 Methodology for application

Production goals in construction generally direct to the optimization of the interrelated target variables quality, schedule, and costs (Borrmann et al., 2018), for which planning reliability and process stability in execution plays a crucial role (Kim and Ballard, 2010). Consequently, methods directed to these objectives, including the LPS, become anchors for production management systems in construction (Hamzeh et al., 2012). Hence, integrating the LPS as foundation for our new production management system with BIM, the design of the BeaM! system technically represents a system integration on data processing level of the two subsystems, BIM and LPS, to deliver new functionalities and exploit synergies.

With regard to new functionalities and in addition to aforementioned individual BIM and LPS strengths, we have identified three major aspects for potential improvement, namely, (1) elements of the Scrum method, as a representative for agile project management (APM) techniques; (2) implementation of a digital Kanban board to use the Kanban method and enhanced visualization capabilities of digital whiteboards; and (3) addition of features of the EVM project control system given that LPS lacks the control for cost performance (Novinsky et al., 2018). The addition of these aspects from other management techniques are explained below.

4.1.1 Adding aspects of Scrum

In the context of project control, the term "Scrum" refers to one of the most used APM techniques in software development and is also recognized in other sectors (Demir and Theis, 2016). In terms of methodology, Scrum aims to address the task of product development in a highly adaptive manner through regularly delivering increments of the product in short cycles, thereby enabling continuous collection of feedback and newly emerging requirements on the product itself (Fernandes and Sousa, 2010). This approach generates a type of "structured" flexibility that is framed by rigorously defined roles within this agile process, namely, the product owner, the Scrum master, and the development team.

After the applicability of APM ideas in construction execution was investigated, Owen and Koskela (2006) suggested the beneficial application within execution process planning but not for site management. By contrast, Ribeiro and Fernandes (2010) stated that agile techniques were suitable for steering all project phases in the context of small- and medium-sized enterprises. Based on these prospects, we want to discover the potential of APM aspects for the BeaM! system.

In particular, we recognize value for adopting the clearly defined roles of Scrum to our proposal. Given that the literature has revealed that the main barriers of successful LPS implementation comprised poor methodological correctness and partial implementation, we perceive that precisely formulated roles with distinct responsibilities in the single process steps improve the proposed production management system. Although the LPS routines of iteratively checking commitments and learning cycles intrinsically cover several agile ideas, we intend to extend the BeaM! system by introducing new roles analogously to the Scrum framework. To establish a parallelism to the game of chess, we call these roles as BeaM!-King and

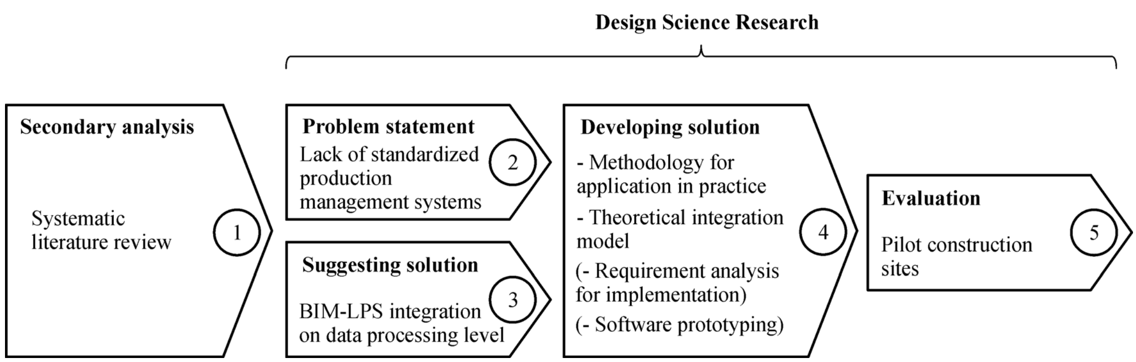

Fig. 1 Followed research strategy.

the BeaM!-Knight, which are described in detail in Section 4.1.4.

4.1.2 Adding aspects of (digital) Kanban

A Kanban system provides information in terms of pull signals along value-adding-chains in manufacturing settings via cards or boards. When applied to the LPS, this system can support the pull planning requisite of task-completion releasing new work (Ballard, 2000b). Through the information provided by the Kanban, task specifications and sequencing are clearly visible to workers or to Last Planners (Matt and Rauch, 2014). One of the core elements of the Kanban method is to limit Work-in-Progress for optimizing flow (Anderson, 2010). We perceive that this method can be beneficial to the BeaM! system to balance load to capacity, which is critical for productivity within a production system (Ballard, 2000a).

Mossman (2013) emphasized the success factor of visualization when LPS is implemented. Therefore, current sticky-notes are standard for a visual representation of the LPS. Modrich and Cousins (2017) hypothesized that the joint use of LPS with Kanban techniques in design fits better than conventional project management approaches. They concluded that the interaction of LPS metrics and Kanban-board metrics improves information flow. We will adopt this hypothesis and extend it to the execution phase by applying our system on digital whiteboards (BeaM!-Board) and enabling Kanban control.

4.1.3 Adding aspects of EVM

Cost control is addressed through introducing EVM elements to the BeaM! system. In particular, BeaM! compares the EVM metrics Planned Value (PV), which represents the budgeted cost of work scheduled (BCWS), and the Earned Value (EV), which corresponds to the budgeted cost of work performed (BCWP). To apply EV analysis in BeaM!, the application of the LPS defines the work that must be accomplished and simultaneously determines the "earning-rules" for deciding whether work has actually been accomplished based on a 0/100 policy. These earning rules are in line with the definition by the Lean Construction Institute (LCI) that says "the Last Planner does not give credit to assignments on the Weekly Work Plan that remain incomplete at the end of the week, even though they may have been started" (Ballard et al., 2007). Thus, any kind of other earning rule of the form $x/100–x$, which indicates that $x\%$ credit is earned when an operation is started and the remaining is earned when it is finished — which is supported by numerous traditional construction project management tools, are not permitted.

With regard to the completion criteria, the LCI stated that "end-of-week completion commitments must be met" (Ballard et al., 2007). Monitoring the actual costs (AC) during execution and comparing them with EV provides insights into the overall cost status. Notably, the Managing by Means (MBM) thinking approach, as defined by Kim and Ballard (2010), will continuously govern the site management. Therefore, the cost parameters solely represent informative attributes of LPS operations. This means that EVM metrics are exclusively understood as additional information about the project status and irrelevant for the workflow. Hence, stabilizing the workflow remains governing which we assume that could be achieved through the LPS mechanism, and thus negate the criticism of EVM representing an enemy of workflow (Kim and Ballard, 2002). This process certainly requires clear measures and signals that support this target-oriented application of the LPS and the process-related visualization of irregularities. We aim to satisfy this requirement through integrating the BeaM! system with the Kanban method and application on digital whiteboards.

Novinsky et al. (2018) and Zhang et al. (2018) have recently investigated the complementary applications of LPS and EVM and disclosed the mutual fit. Given that the positive findings of Novinsky et al. (2018) were merely related to the design phase, we intend to extend the joint application to the execution phase.

4.1.4 Bringing the parts together

To integrate these aspects of existing management techniques with the BeaM! system, we apply method engineering principles to develop a methodology for application as a new artifact that is consistent with the applied DSR strategy. In particular, the guidelines for designing an agile methodology according to Highsmith (2002), who was significantly involved in the emergence of the agile manifesto (Trepper, 2012), are applied in an adapted form. Highsmith (2002) argues that the design or adaptation of an agile method should be based on characteristics, which enable a method design that goes beyond strictly defined processes and elements but leads to a holistic ecosystem for application. Therefore, BeaM! is embedded in a holistic ecosystem. This ecosystem is characterized by defining the new process and emerging roles, thereby also scoping the domain of application and formulating underlying ideals and principles. Figure 2 lists the parts of this ecosystem.

The process of how to apply BeaM! in practice is depicted in Business Process Model Notation (BPMN) in Appendix A.

In terms of processes and consistent with the LPS, the starting point for phase planning is a master schedule with milestone representations. The master schedule, together with contractual documents, bills of quantities, and the coordinated BIM model in the IFC file format, is assumed as given input. Generally, the BeaM! process follows the five-step logic of the LPS but is consistently digitally

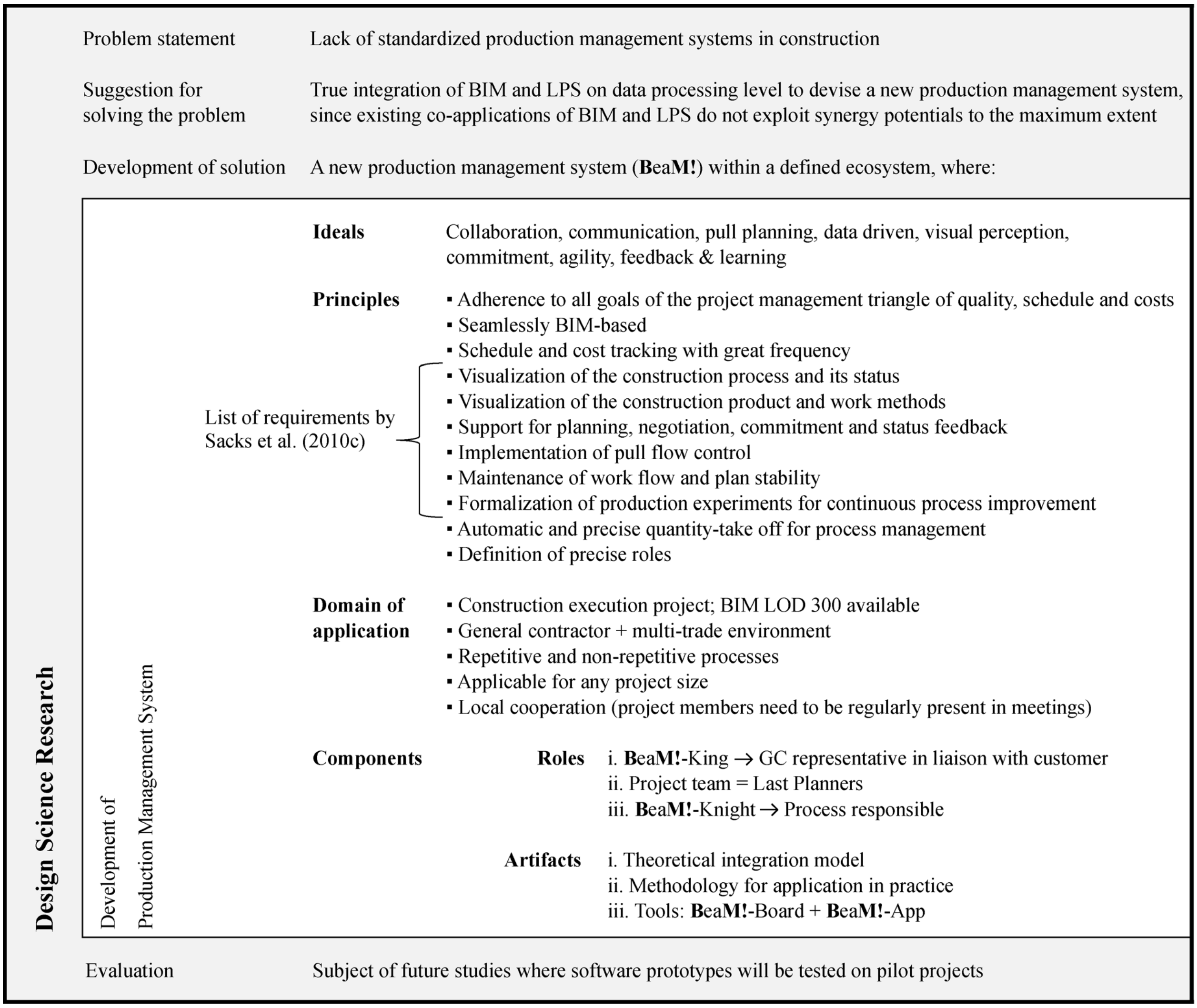

Fig. 2 Formulation of the new production management system as methodology: BeaM!.

supported and linked to associated BIM objects apart from non-digital master schedules. In addition, the LPS is extended in terms of methodology. That is, the sticky notes, which describe the process of the Digital Process Kanban (DPK) can be individually created by the Last Planners on their cell phone via the BeaM!-App during phase-planning. Subsequently, DPK can be literally "beamed" to the BeaM!-Board and serve as pool for the cooperative phase planning (Fig. 3).

Prior to or during planning phases, estimated costs are associated to each DPK, which represents the PV with respect to EVM. In contrast to the proposal of Novinsky et al. (2018) and Zhang et al. (2018), the underlying quantities should not be estimated but should constitute a provided information as an inherent part of the linked BIM objects.

Further DPK can be added to the board anytime when the pull planning process reveals other prerequisites or hand-offs. Using own cell phones for creating the Kanban reduces resistance for standing up, labeling, and attaching sticky-notes to the board. The corresponding BIM objects can be selected in the BIM viewer and linked to the DPK. Another possibility is to initially select the BIM objects in the viewer via touch control and subsequently create a linked DPK. Under both cases, the BIM-linked DPK are available for phase planning based on the LPS, wherein the Last Planners are supposed to be actively involved. During non-digital pull planning sessions, we experienced that arranging sticky-notes on a board generates significantly less resistance than creating them. Thus, a lively collaboration can be assumed when the DPK is already present on the board.

In the subsequent steps that foresee look-ahead planning and WWP and according to the nomenclature of task granularity provided by Hamzeh et al. (2012), DPK are the starting point to transform processes into assignable operations. These operations are represented through new digital sticky-notes, namely, Digital Operation Kanban

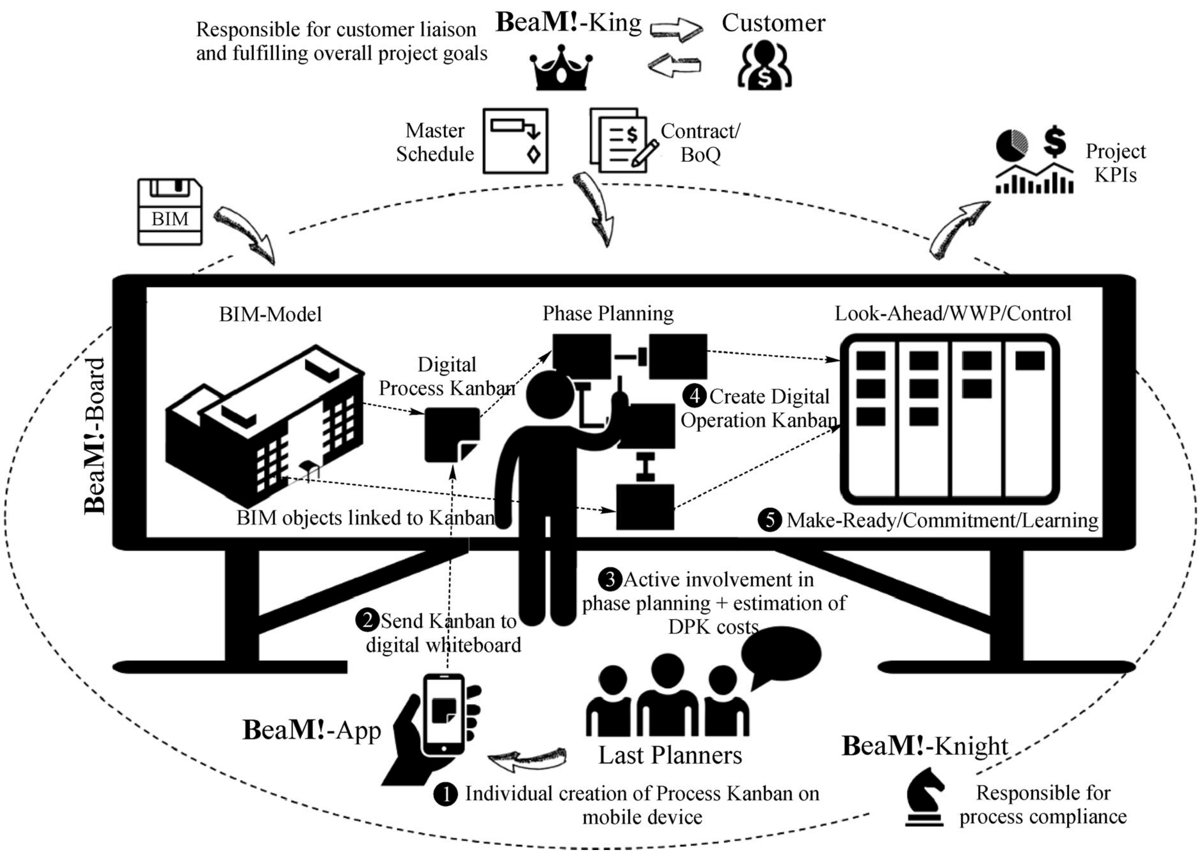

Fig. 3 Schematic representation of BeaM!.

(DOK), which maintain the link to the respective BIM objects and quantity information. For instance, the DPK of producing a concrete slab is transformed into multiple DOK such as formwork construction, reinforcement placement, and concrete pouring, which still direct to the same BIM objects. With respect to quantities of operations, algorithms can be applied to the DOK for approximate calculations. For example, the quantity in terms of steel tons for the operation of reinforcement placement could be approximated as an order of magnitude to 10% of the related concrete volume (m^3) under numerous cases. The definition of such calculation rules should be subject to discussion among Last Planners during look-ahead planning sessions, wherein their experience from practice is purposefully leveraged. In terms of costs, Last Planners should distribute the PV assigned to DPK to the subordinated DOK on a percentage basis.

With regard to the introduced roles, the BeaM!-King is responsible for creating phase schedules in accordance with the objectives of the milestone plan and the customer. However, he/she has limited action possibilities to intervene in the BeaM! process itself in line with the established chess parallelism. This role is proposed to be played by the project or site manager of the General Contractor (GC). In addition, the role of the BeaM!-Knight can be played by either a GC representative or an external consultant. The BeaM!-Knight is primarily responsible for ensuring process compliance and thus controlling the methodological correctness of the individual LPS steps. Analogous to the name-giving chessman, the BeaM!-Knight has the possibility to jump back and forth on the "playing board" and intervene where necessary. Content definition for DPK and DOK does not fall within his/her merit. Moreover, the BeaM!-Knight is responsible for moderating and operating the BeaM!-Board during look-ahead and commitment planning as well as during control sessions and communication of Key Performance Indicators.

With regard to the control stage of LPS, in addition to the typical checking of commitments and analyzing root causes at the end of each week, and as an extension of the regular LPS, the Earned Values of each completed DOK are summarized and used for evaluating the current project performance in terms of costs.

4.2 Theoretical integration model

To formulate a theoretical integration model between BIM and LPS, the IFC data structure for BIM data exchange is considered. The IFC data structure offers the storage spaces of the IfcProcess and IfcTask classes as subclasses of the superclass IfcObject (Borrmann et al., 2018). The inheritance from the IfcProcess class enables the definition of dependencies between tasks using IfcTask instances through specifying the IsPredecessorTo and IsSuccessorFrom attributes (Braun, 2013). According to BuildingSMART (2019a), "an IfcTask is an identifiable unit of work to be carried out in a construction project." Since the introduction of IFC version 4, start and end dates can explicitly be assigned to these instances and durations can be specified through the TaskTime (type: IfcTaskTime) attribute. Using the IfcTask class, one can assign multiple tasks to a single BIM object and thus map complex technological construction sequences to it (Braun, 2013).

To establish a link to BIM objects and prepare them for any kind of manipulation within the BeaM! system, the IFC data structure is converted into an executable program structure using high-level object-oriented programming languages such as Java or C++ . To this end, we use open source IFC binding libraries to create a system that is independent from commercial BIM authoring software. The integration model is presented according to the steps of the LPS, and the link to a BIM model is displayed through association on data processing level with respect to the IFC file format.

4.2.1 Master schedule

The master schedule with milestone representation is assumed as a given input. It can be provided either digitally or as non-digital print-out. The master schedule is not necessarily linked to the BIM model.

4.2.2 Phase scheduling

In Table 1, phase planning steps 1–6 defined by Ballard (2000b) are associated to manipulations of an IFC-file as the representative of a BIM model on data level. Moreover, the process of how these manipulations are conducted using the BeaM!-Board as a digital whiteboard is described.

4.2.3 Look-ahead planning

The look-ahead window regularly comprises six weeks prior to execution and foresees to break down processes into assignable operations when this window is entered. In addition to process breakdown into operations, the process of look-ahead planning is characterized by identifying constraints for these operations and sequencing them using first-run studies. Constraints are eventually removed three weeks prior to the planned execution; thus, operations are made ready for execution. With regard to the IFC data structure, constraints are of the entity type IfcConstraint and linked to IfcTask objects through IfcRelAssociatesConstraint relationship instances. According to BuildingSMART (2019b), "an IfcConstraint is used to define a constraint or limiting value or boundary condition that may

Table 1 Mapping phase planning according to Ballard (2000b) to the IFC data structure

Step	Phase scheduling steps 1–6 by Ballard (2000b)	BIM: IFC manipulation	Digital Kanban board functionality
0	Have a master schedule as starting point and identify milestones	Instantiate IfcTask object and set Boolean IsMilestone to true	Select BIM objects in IFC viewer and press "create Milestone" button
1	"Define the work to be included in the phase, e.g., foundations, building skin, etc."	Kanban trigger instantiation of IfcTask objects, which are linked to selected BIM objects (IfcElements) through IfcRelAssignsToProduct objects	Select BIM objects in IFC viewer and press "create Digital Process Kanban" button OR create corresponding Digital Process Kanban on mobile device and send it to BeaM!-Board and link it to BIM objects
2	"Determine the completion date for the phase, plus any major interim releases from prior phases or to subsequent phases"	Set attribute LateFinish of type IfcDateTime in entity IfcTaskTime and relate to milestone IfcTask objects in Step 0	Click on respective milestone and set the finish date
3	"Using team scheduling and stickies on a wall, develop the network of activities required to complete the phase, working backwards from the completion date, and incorporating any interim milestones"	Manipulate the IsSuccessorFrom and IsPredecessorTo attributes of IfcTask objects defined in Step 1	Arrange Kanban via touch control on BeaM!-Board defines dependencies
4	"Apply durations to each activity, with no contingency or float in the duration estimates"	Assign duration through the ScheduleDuration attribute of IfcTaskTime entity and relate to IfcTask objects defined in Step 1	Click on respective Kanban and set duration
5	"Reexamine logic to try to shorten the duration"	Update of dependencies according to re-arrangement	Collaborative rearrangement of Kanban on BeaM!-Board
6	"Determine the earliest practical start date for the phase"	Set attribute EarlyStart of type IfcDateTime in entity IfcTaskTime and relate to initially arranged IfcTask object in Step 5	Click on first Digital Process Kanban of the phase and set the start date

be applied to an object", which fits the description of Constraints Analysis and Removal by Ballard and Tommelein (2016). When constraints are formally removed during look-ahead planning, the relationship to IfcTask is removed on data processing level.

Operation design from the perspective of the BeaM! system consists of transforming DPK into the DOK. On data processing level, the system internally filters all DPK with a start date within the look-ahead window and selects them on the BeaM!-Board for operation design. The associated BIM objects are highlighted in the BIM viewer as a visual support. The relationship between operations and processes is technically represented by IfcTask objects that are nested in other IfcTask objects through the nesting relationship IfcRelNests. The operation objects possess a Status attribute of the type IfcLabel. This attribute can be a free text which will have the value "not ready" by default.

4.2.4 Commitment planning (Weekly Work Plan)

Operations that have been committed to by the Last Planners during WWP only change their Status attribute from "not ready" to "committed" when all IfcConstraint objects are detached from these operations on data processing level. Thus, the operations become part of the next WWP. If constraints are removed but no commitment is made by the Last Planners, then the Status attribute changes to "made-ready". This operation can subsequently become part of the workable backlog when the Last Planners reach an agreement that its execution will not negatively affect workflow. The Status attribute of the operation changes accordingly to "workable backlog" in this case.

Transforming operations that CAN be done into operations that WILL be done, a committed-to-be-built-BIM (CTBB) model can be generated with consideration of the WWP containing all committed operations for the subsequent week. Thus, an As-built-Forecast-BIM-model is implicitly developed for workers on site as a visual indicator for what must be done for the next week. During the following control and learning phase, whether the components specified by the CTBB model are actually built can be checked on site. However, a coordinated BIM model with at least a Level of Development 300 is required to ensure a controllable minimum information content.

4.2.5 Monitoring and learning

The LPS metrics, namely, PPC, Tasks Made Ready (TMR), and Tasks Anticipated (TA) are supplemented by the interplay of the EVM's metrics, namely, PV, EV and AC and the Kanban metrics such as average cycle-times (CT) and lead-times (LT), which are derived from cumulative flow diagrams (CFD). The integration with the BIM model is exploited by the fact that CFDs can display the cumulated consumed materials in addition to the amount of operations in a given state (e.g., made-ready). Thus, further support, including support for the control of material allowance on site, is represented.

The metrics represent total project measures but can be broken down to different tiers according to Ratajczak et al. (2018). The process status of single DOK is stored in the IfcTask Status attribute and serves as a query parameter for the construction progress visualization in the BIM viewer. The possible values for the Status attribute of operations are defined within the BeaM! system as (i) not ready, (ii) made-ready, (iii) workable backlog, (iv) committed, and (v) done. Here, the status "done" refers to operations that have been "done as committed" and thus affect the metric of PPC positively. If an operation has not been done as committed, a reason for non-completion (RNC) must be provided from a predefined list.

4.2.6 Extended conceptual model

The provided description on how to apply the BeaM! system in practice and how to link LPS process information to IFC entities is abstracted into an extended conceptual model as an adaptation and extension of the LPS scheme of Ballard (2000a) (Fig. 4), which also comprises a connection to existing theory. This extended conceptual model was devised on the basis of the findings of an integrative literature review on LPS and BIM integration during the construction execution phase, which is drawn upon empirical literature (Schimanski et al., 2020). Integrative literature reviews are type casted through analyzing, criticizing, and integrating a certain literature sample that enables the deduction of new models or frameworks (Torraco, 2005).

The extension of this conceptual model is characterized here through the addition of the EVM aspects and the exact definition of roles within the BeaM! system.

For further explanation, it can be stated here that the integrated EVM aspects comprise a framework for cost tracking which has no impact on the production planning itself but provides merely additional status parameters. The BeaM!-King is responsible for aligning what SHOULD be done from the customer perspective to what WILL be done and to what has been done (DID) as the result of the Last Planner process. The BeaM!-Knight moderates the Last Planner process. The BIM model represents an information source for the Last Planner process and a visualization instrument for the current and planned status of the project. The digital Kanban system serves for status visualization, too. In addition, this Kanban system helps to define what CAN be done by balancing load visually to capacity and thus supports to reduce Work-in-Progress that WILL be done.

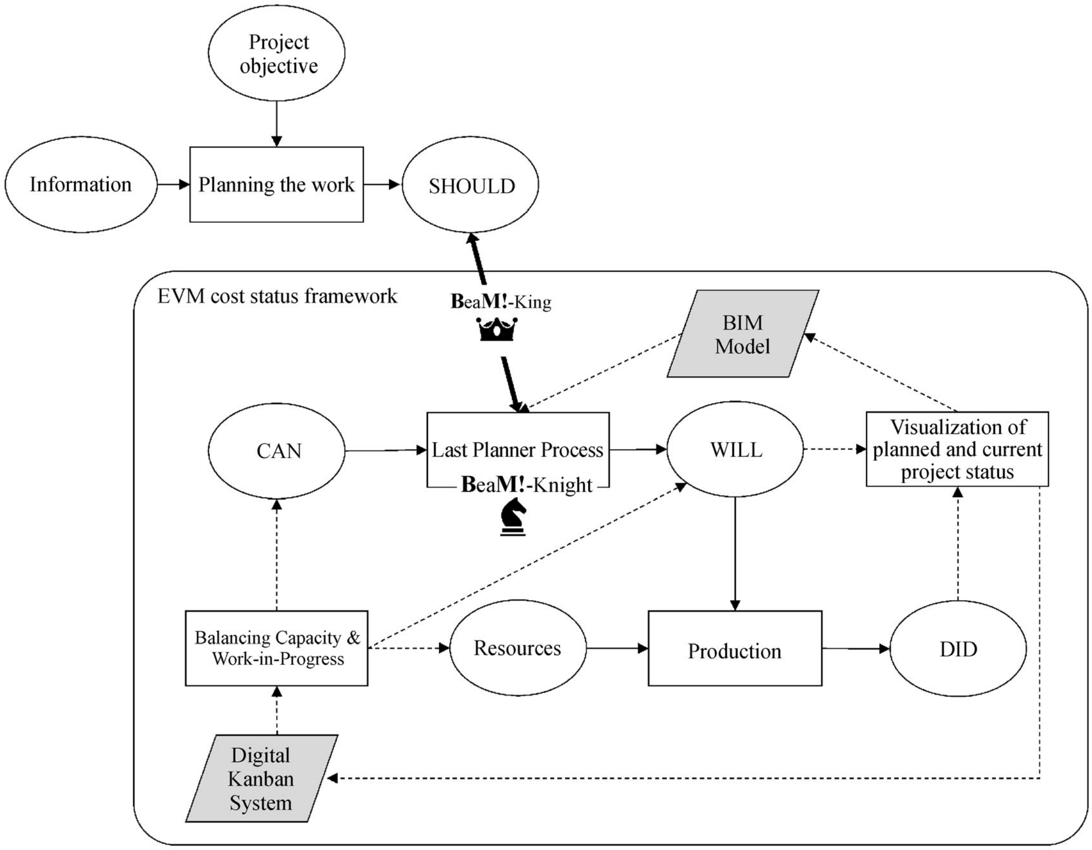

Fig. 4 Conceptual model of BeaM!.

5 Discussion, conclusions, and outlook

This design of the proposed production management system aggregates different existing and well-proven management techniques that are used in construction. EVM provides methods to determine whether a project is running well in terms of cost variances. LPS comprises the actual basis for production planning and control and offers the instruments to define whether and when value has been earned. Moreover, it provides a framework for enhanced process stability and workflow reliability, thereby increasing the probability of “earning” as much as planned. The implementation of this combined system on digital Kanban boards and leveraging the Kanban method itself through limiting Work-in-Progress and visualizing the flow of work emphasize the pull planning characteristics of the LPS.

The missing piece in this puzzle is BIM. On the one hand, BIM provides quantities and information to estimate durations and costs of construction processes. On the other hand, it serves as an enhanced basis for decision-making in phase and look-ahead planning session and as a medium for intuitive visualization of the status of a project. These features are unified in the BeaM! production management system.

Therefore, a theoretical model for system integration on data processing level is proposed in this paper. Such a system will be used as a starting point to develop software prototypes to prepare BeaM! for pilot construction projects and thus for evaluation according to the applied DSR strategy. Furthermore, a methodology for application in practice of the BeaM! system and the underlying ideals, operational principles, the domain of application, and new roles in allusion to Scrum in line with Highsmith (2002) were introduced. Thus, the BeaM! system fully embodies the Lean philosophy and simultaneously functions as a complete production management system harmonizing the target values of quality, schedule, and costs with a rigorous adherence to digital working procedures.

Our future studies will address the limitations of this study and incorporate EVM and Kanban information into the presented integration model with respect to the IFC data structure, which is currently absent. Given that this paper represents the extended version of a conference contribution (Schimanski et al., 2019), wherein we merely proposed the theoretical integration model and the methodology to the scientific community to collect preliminary feedback, the concepts should still be scientifically validated.

This limitation will be addressed within the evaluation phase, wherein the workability of the proposed production management system is tested and thus contribute to bridge theory and practice and evaluate the applicability and utility of the solution on the basis of the DSR approach (Khan and Tzortzopoulos, 2018). Thus, the findings of the evaluation phase will help assess whether the stated problem of missing standardized and BIM-based production management routines can be (partially) solved through our proposed solution.

The added aspects of Scrum and Kanban within the Last Planner® System that are suggested in this study will be investigated during the evaluation phase in practice. Furthermore, the role of EVM that is applied together with the LPS within BeaM! will be subject to in-depth analysis to prove the hypothesis that EVM may be a friend of workflow if the requirements outlined in this study are satisfied.

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Appendix A

Business Process Model Notation (BPMN) of the BeaM! system.

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