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BIM-based Last Planner System tool for improving construction project management

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A R T I C L E I N F O

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A B S T R A C T

The Architecture, Engineering & Construction (AEC) industry strongly affects the economy, the environment, and society as a whole. However, when compared to other industries, its productivity, over recent decades, has been very low. Currently, the AEC industry is undergoing major changes, mostly driven by the implementation 安装启用 of Building Information Modeling (BIM), and the integration of new technologies. When coupling these with 精益原则 Lean principles, there is the potential to improve the productivity and efficiency of construction projects. Although Lean Construction and BIM are approaches with quite different initiatives, both have a profound impact on the industry. Many studies have shown the advantages of the Last Planner System (LPS), yet its integration with BIM technology has not been fully exploited. The Last Planner System of Production Control – a production planning system designed to produce a more reliable project plan – and the principle of promoting continuous improvement are introduced. By capitalizing on the synergies between Lean Construction and BIM, this study proposes a construction management tool that combines the LPS with the 3D visualization of construction projects to improve productivity and reduce construction waste. The prototype tool is mainly aimed to be used as a construction management tool during the construction phase. The tool allows dividing construction projects into work zones, obtaining a fully automated quantity take-off, and offers a color-coded 4D construction simulation for the short-term planning process of the LPS. It allows for a systematic evaluation and analysis of the construction planning in terms of productivity, manpower allocation, and quantification of waste considering the short-term planning process, which promotes continuous improvement of future construction planning.

1. Introduction

In the last 50 years, the productivity in the Architecture, Engineering & Construction (AEC) industry has dropped by almost 20%, while the productivity on non-farm business companies has grown by over 150% [28]. The AEC industry has missed the opportunity to adapt to the digital revolution that significantly improved productivity, cost-efficiency, and sustainability in other industries. However, the AEC industry is in the throes of change. Large capital investments in digital solutions and first movers establishing future technologies across the entire construction value chain are a clear indication of that change. With the implementation of Building Information Modeling (BIM) and Lean Construction, the AEC industry is undergoing a significant transformation. Both are approaches with different initiatives, but both have a profound impact on the industry. So far BIM and Lean Construction have been used separately as key approaches to increase the overall productivity and efficiency of the AEC industry. However, various studies by Sacks et al. [26], Oskouie et al. [22], Hamdi & Leite [11], and Dave et al. [9] have indicated that there are synergies, which can efficiently enhance the productivity of construction projects by applying

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both approaches simultaneously.

This paper introduces a BIM-based tool that supports the Last Planner System® of Production Control [1]. The developed tool is aimed to be mainly used as a construction management tool to integrate the process and product visualization, eliminate the amount of construction waste, and improve the efficiency and reliability of the construction management process. It should be noted that the tool has been developed as a prototype to prove the concept of the interaction of Lean Construction and BIM and it is not a commercially available software. Section 1 provides a summary of the theory of Lean Construction, the foundations of the Last Planner System and the Lean principle to promote continuous improvement. Section 2 goes over the interaction between Lean and BIM, focusing on previous work and existing software. In Section 3, the structure and main features of the BIM-based LPS tool, are presented and implemented in Section 4 using a multistory pilot project. The conclusion is presented in Section 5, in which limitations and future research work are also included.

1.1. Building Information Modeling

Although there are a number of definitions for Building Information Modeling, for this study Sacks et al. [25] definition has been chosen. Sacks defines Building Information Modeling (BIM) as "a modeling technology and associated set of processes to produce, communicate, and analyze building models." Special emphasis should be given to the process part of BIM, and not the model itself. In particular, BIM provides a collaborative decision-making platform to facilitate information sharing for model simulation and project management. It also helps to reduce miscommunication and errors among construction players (Isikdag & Underwood [15] and Chen & Hou [7]). With this context as a background, the BIM processes and features have the potential to support Lean Construction principles which sets the framework for this study.

1.2. The foundations of Lean Construction

It was a long time before the AEC industry adopted Lean Production methods. The excuse offered was that, unlike the state-of-the-art automobile industry, it is not stationary producing. On the contrary, the AEC industry is producing stationary objects, which, to a certain extent, are too large to be moved [4]. Koskela, Howell, and Ballard's analysis of construction productivity and delays in the 1990s, covering a wide range of projects and types indicated a 54% average plan failure [2]. This means that the conventional project management methods (Work Breakdown Structure, Critical Path Method, Earned Value Analysis, etc.) fail to deliver projects on time, on budget, and with agreed quality [3]. Based on these results, Koskela [17] showed that most of the problems could be solved through an all-embracing project and production management system by applying the Toyota Production System (TPS). Lean Construction is the adaption of the TPS. It is used to optimize processes in all kind of fields, ranging from concept development, to concept design, to production, and even operation and management [18].

1.3. The Last Planner System of Production Control

Projects with conventional scheduling methods show a gap between long-term project planning and short-term execution planning. Since the time span before the execution of the task is not planned in detail, resources and information cannot be provided on time, and constraints cannot already be eliminated at an early stage. Today's construction projects are complex, burdened by many uncertainties, and subjected to changes in planning. The more detailed a forecast is, and the more a forecast looks into the future, the less accurate it will be [20]. It is also unable to predict the day on which a specific task will be executed. Instead, it is certain that the day of execution will not be the scheduled

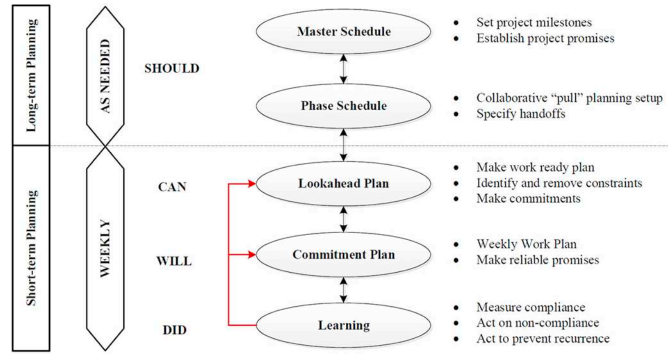


Fig. 1. The planning stages of the Last Planner System of Production Control (adapted from [5]).

day predicted several years ahead [4]. In 1992, Ballard started to develop the Last Planner System (LPS) which was further developed by Ballard and Howard to improve the planning dependability, increase the construction productivity, and ensure a smooth workflow without disturbances [12]. Now, the LPS serves as a critical element of project production control in Lean Construction. The LPS is a comprehensive "pull" system for the optimization of the planning and the execution of construction work. It includes a cooperative planning process as well as an analysis of incorrect planning. This achieves excellent cooperation in the production process and establishes a sound basis of trust, which is a necessity for the on-time completion of the project. The project planning of the LPS is divided into two different stages (Fig. 1) – the long-term planning stage and the short-term planning stage [5]. The long-term planning phase consists of the Master Schedule and the Phase Schedule, which are adjusted as needed to specify what *should* be done.

The Lookahead Plan bridges the gap between long-term project planning and short-term execution planning. The frequency of the planning is weekly. The planning time-frame, which is related to the nature of the project, is usually six weeks since most construction-related problems can be eliminated within this period. The goal of the Lookahead planning is to make plans more realistic as construction tasks approach execution, exposing as many problems as possible, as early as possible. The Lookahead Plan is used to decompose activities from phase level to operations level. The purpose differs depending on the progress of the Lookahead Plan (Fig. 2). Lookahead planning is used to perform first run studies (virtually or physically), identify constraints, assign responsibilities, communicate workflow processes, and prepare the information and resources. In so doing it makes the tasks ready that *should* be done, so that they *can* be done [13]. Lookahead planning uses activity screening and pulling [12] to identify and remove the constraints. Screening exposes the activities to constraint analysis and used to decide which activities should be allowed into the

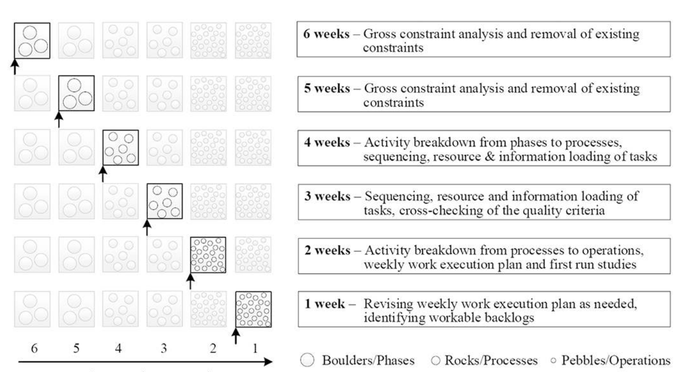


Fig. 2. The six-week Lookahead planning process in the Last Planner System (adapted from [12]).

six-week Lookahead Plan and which ones should be allowed to move forward. Pulling is used to remove constraints and ensures the availability of prerequisites as per the actual demand. During the screening process tasks are grouped into three different task states:

(1) "task ready" if all constraints are eliminated, and the task is ready for execution,
(2) "task can be made ready" if the task is actually constrained but will most likely have all constraints removed in time, and
(3) "task cannot be made ready" if the task will not have its constraints removed and will not be executed as planned.

The Commitment Plan, also known as the Weekly Work Plan (WWP) is the most detailed plan in the LPS. The Commitment Plan specifies the individual work steps that *will* be done, as well as the interdependences between the various contracting parties. To ensure the reliability of the Commitment Plan, the tasks must meet the following four quality criteria: definition, soundness, sequence, and size [4].

The phase of Learning describes the completed work. It is considered as a tool for future planning optimization by tracking the performance of the short-term planning process to improve the productivity and efficiency of the project. That is done by comparing *did* to *can* and *will* and using these observed values for continuous improvement [12]. The reliability of the commitments made is measured to monitor and improve the productivity after each week of execution.

1.4. The lean principle to promote continuous improvement

Based on the concept of the TPS to increase the output value through systematic consideration of the customer requirements while reducing the share of non-value-adding activities [21], Koskela [16] defined the principles forming the major foundation of Lean Construction to reduce construction costs and time, as well as improve construction productivity and efficiency. Among these principles, particular attention is given to the principle to promote continuous improvement into the process. Continuous improvement is a method for identifying opportunities for streamlining work and reducing waste in the form of cost, time and rework [19]. The implementation of continuous improvement uses Kaizen. Kaizen is defined by the four-step model "Plan-Do-Check-Act" (PDCA) (Fig. 3) – and can be applied in the Learning Phase of the LPS.

The core principle of the continuous improvement process is the self-reflection of the existing processes. By applying Kaizen, improvements are based on many small changes, which are less likely to require significant capital investment than major process changes, and therefore easy to implement. All employees should continuously be seeking ways to improve their performance, which helps encourage workers to take ownership of their work, reinforce teamwork, and thereby improve work motivation.

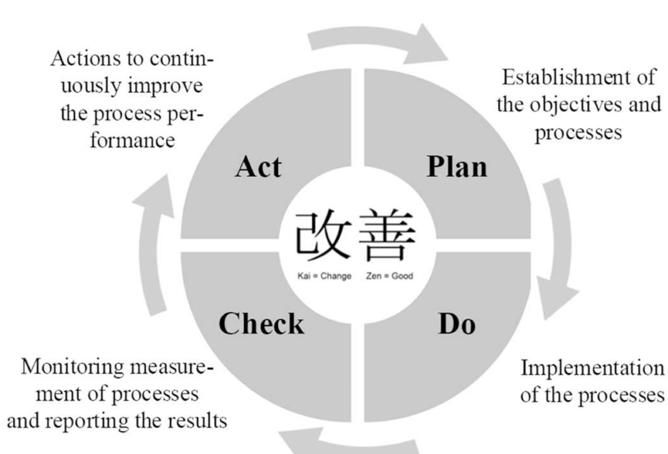


Fig. 3. The Kaizen continuous improvement PDCA-cycle (adapted from [5]).

2. Interaction between Lean and BIM

Lean Construction is a construction management philosophy focused on creating value for the customer and eliminating non-value adding activities. Whereas, BIM is mainly focused on applying information technology over the entire project lifecycle [10]. Although the application of Lean Construction and BIM is not dependent on each other, studies by Oskouie et al. [22], Hamdi & Leite [11], and Dave et al. [9] have already indicated that their interaction enables various opportunities to create a more efficient workforce and more effective processes of construction projects as well as challenges in its implementation. A significant contribution of assessing the interaction between Lean Construction and BIM was made by Sacks et al. [26]. Sacks defined a matrix in which the principles of Lean Construction are matched to the functionalities of BIM to evaluate the contribution of BIM as a visualization tool in Lean Construction. In this study, significant synergies were identified, which were backed up with empirical evidence. By reviewing Sacks et al. [26] matrix, the following Lean principles with the highest concentration of unique interactions were defined:

a) Get quality right the first time (reduce product variability)
b) Focus on improving upstream flow variability (reduce production variability)
c) Reduce production cycle durations

The BIM functionalities with the highest concentration of unique interactions were defined:

a) Aesthetic and functional evaluation
b) Multi-user viewing of merged or separate multi-discipline models
c) 4D visualization of construction schedules
d) Online communication of product and process information

Realizing that the BIM functionalities a), b), and d) are mostly concerned with the field of construction management it can be asserted, that integrating the Lean Management approach with the technical capabilities of BIM will bring benefits to the overall productivity and efficiency of construction projects and enhance the planning process in the LPS [26]. However, even decades after adopting the Lean Production System in the AEC industry, commercial software does not fully support the LPS. When applying the LPS to construction projects, it is common to use sticky notes and self-created spreadsheets without making use of the added value of holding the data in a cloud-based data system – also with regards to subsequent projects. This lack of commercial BIM software integrating Lean has been tackled in previous research: Sriprasert & Dawood's [27] Lean Enterprise Web-based Information System (LEWIS), Dave et al.'s [8] VisiLean tool, and Sacks et al.'s [24] KanBIM Workflow Management System. All research methods developed and tested a prototype construction management tool. To capitalize on these synergies and promote the combined use of Lean and BIM a prototype tool was developed to provide the integration

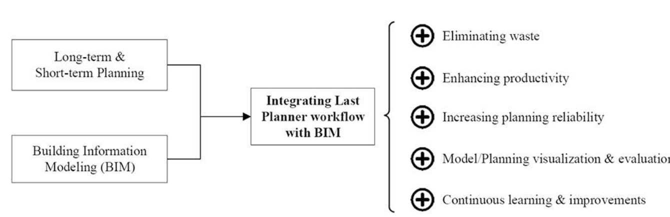


Fig. 4. The objectives of the integrated Lean Management approach using BIM.

of the LPS workflow using BIM. The developed tool meets all basic requirements of commercial BIM software and covers the functional requirements and features of previously developed research projects. In addition, it offers unique planning visualization and planning evaluation features, particularly related to the short-term planning phase and the Learning Phase. Commercial BIM software and previous research software dealing with the integration of the Lean Management approach do not take advantage of the possibilities provided by an object-oriented and cloud-based project controlling process. By storing the as-built data together with the geometric building model data in the same file or database, a truly powerful synergy of information is generated, which greatly supports the Learning Phase, enhances the reliability of the planning process and leads to a veritable continuous improvement in the short-term planning phase, as presented in Section 4. Although almost all commercial software packages facilitate the entering of as-built data, these data do not take on an informative character in the software. This means that the data are not used for further process planning optimization. If used at all, the data are only considered for an as-built 4D construction simulation. Nevertheless, a comparison of the different features of the software with the features of commercial software such as Synchro or Vico is beyond the scope of this study, mostly due to the limitation of the authors to acquire and test all commercial software.

The objectives of the prototype tool are shown in Fig. 4. These objectives consist of the Lean fundamentals, BIM functionalities with the highest concentration of unique interactions, and further Lean principles that are considered as fundamental for the management of construction projects during the execution phase.

3. BIM-based LPS prototype tool

The features of the prototype tool were derived from the definition of the objectives. The tool supports the LPS, including the six-week Lookahead Plan, the Commitment Plan, and the Learning Phase. The features of the tool comprise of a wide range of project management knowledge areas, such as Integration, Scope, Time, Human Resources, Communications, Risk, and Procurement [23], relevant during the execution of construction projects. Fig. 5 shows the main features of the tool in relation to the objectives. By linking the tool features with the objectives, the tool shows great interactions between the individual items. Particular attention was given to the objectives being addressed by multiple features.

Although the tool includes features similar to those available in commercial project management software, such as quantity take-off and 4D visualization, it provides a unique way to use those features by taking into account the LPS and supporting Lean principles. Other features such as construction zoning, model and task information using the as-built data, and construction planning evaluation are unique to its implementation.

The application of the BIM-based LPS tool results in the necessity of coupling different time components: the BIM planning and the construction planning process. Thus, it is essential to define the level of detail (LOD) of the BIM model that is required at each stage of project development in the BIM Execution Plan (BEP) at the beginning of the project. The LOD is composed of the geometric information (Level of Geometry) and the semantic information depth (Level of Information) which increases as the project progresses from a simple design intent model through to a detailed virtual construction model. This not only ensures that the BIM model is developing in sufficient detail, but also the information required by third parties, such as the project planner and the construction management team, is provided correctly.

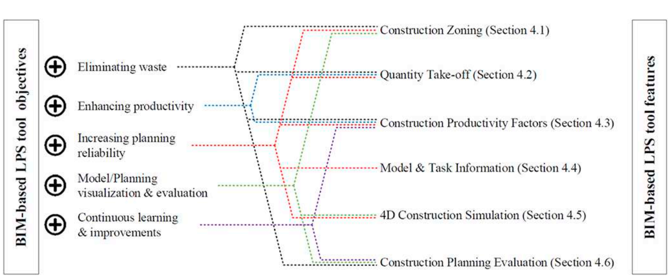


Fig. 5. Implementation of the objectives in the BIM-based LPS prototype tool.

The BIM-based LPS tool is aimed to be used as a construction management tool during the construction phase of a project. It imports 3D Models from an industry foundation classed (IFC) file created with Autodesk Revit. An IFC file is an open file format that contains building information, such as beams, columns, slabs, and doors, as well as their material properties. IFC files are used for interoperability between industry standard BIM software. IFC files can be read by Autodesk's Revit, Tekla's BIMsight software, and Bentley - to mention a few. All IFC files that have been read and uploaded by the tool are automatically stored in a MySQL database. Using a MySQL database allows for an easy migration to use Cloud computing. The imported construction schedules use the extensible markup language (XML) format files exported by MS Project. Any other project scheduling software that exports its scheduling data in XML format files (such as Primavera P6 or PowerProject) could also have been used. The XML file format is a plain text file used to create common information formats and share both the structure and the storage of data.

3.1. Model & schedule linking

The tool uses an automated way to link the objects in the 3D Model with the construction schedule. Each object in the 3D Model is associated with information about the assigned construction zone (Z:), the level (L:), the building type (T:) and also defined by a unique seven-digit ID number (Revit ID number). While the construction zone must be assigned manually (Section 4.1), the level and the building type are both assigned automatically. Similarly, the same information is given to each task of the construction schedule, by creating a unique task identifier. Tasks with a "boulders/phases"-level of planning detail (Fig. 2) cannot yet be linked with the objects of the 3D Model because the level of planning detail is insufficient. These tasks only contain information about the respective floor in which the work takes place, but do not take into account that the construction of the shell and the interior takes place at a different stage of the project. When assuming a "rocks/processes"-level of planning detail (Fig. 2) – four and three weeks ahead of construction – the objects of the 3D Model and the schedule are linked by the identifier key construction zone, level, and building type. By way of example, the linking of the column elements located in Deck 5B in construction zone 2 is achieved by the key Z:2 L:5B T:Column. By increasing the planning level of detail to the "pebbles/operations" (Fig. 2) – two weeks, one week ahead, and the week of construction –, the Revit ID number is additionally taken into account. Thus, the slab element highlighted in Fig. 7 (ID number 1994801, located in Deck 4A in construction zone 1), the task of the individual object is identified by the key Z:1 L:4A T:Slab ID:1994801. In general, the automated model and schedule linking is similar to the functions of existing commercial software such as Autodesk Navisworks, Vico, or Synchro, and could be used with any modeling software. The automated matching reduces linkage complexity and the risk of manual mistakes and requires less manual input since no rules for matching or element sets have to be defined. Also, subsequent elements created in the 3D model can be identified immediately, because they are not yet assigned to a construction zone. Thus, these elements are clearly identifiable, both in terms of color (Section 4.1) and in the object tree-view (Section 3.2).

The tool is using the Revit generated ID number from exported IFC files. For the purpose of testing and demonstrating the validity of the tool, it is easier to search on the Revit ID number within Revit than it is to search on the 22 character length IFC-GUID[1] (Global Unique Identifier) within Revit. However, since both identities are unique, small adjustments could be made to use the IFC-GUID instead of the Revit ID number. When using the IFC-GUID, the tool would allow the import of IFC files created with any other modeling software.

3.2. Object tree-views

The tool supports the representation of the building objects in multiple tree-views. The tree-views are set up in three different groupings: (a) by Component (Building Type), (b) by Building Level and (c) by Construction Zone (Fig. 6).

The various tree-views show the objects of the overall project, the objects being planned to be constructed in the individual weeks of the short-term planning phase (Commitment Plan and Lookahead Plan – until the "rocks/processes"-level of planning detail) as well as the tasks, which have already been constructed (to address the Learning concept). In this way, an accurate overview of the objects planned to be constructed within the following weeks of construction is created. The specifications of the level of planning detail from Fig. 2 is also applied to the structure of the object tree-views. The tree-views related to a "rocks/processes"-level of planning detail do not consider the lowest level of the tree-view structure, which corresponds to the individual objects and contains the object ID number. However, due to the reduced level of planning detail, the Lookahead planning (i.e., five and six weeks ahead of construction) cannot be correctly represented in the object tree-view by Component (Fig. 6(a)). The tree-view representation creates a clear overview of the object breakdown structure of the project and the weekly short-term planning construction programs. In comparison, the traditional Gantt charts or schedule list-views, typically used in commercial and research construction management software, can become difficult to comprehend, especially for people who are not employed in the field of project planning and scheduling. Additionally, the objects in the tree-views and also the individual tasks in the timeline are highlighted accordingly to the LPS task status – task ready (green), task can be made ready (orange), and task cannot be made ready (red).

```
Project          Project          Project
└─Type           └─Level          └─Zone
  └─Level          └─Type           └─Level
    └─Object         └─Object         └─Type
                                        └─Object
   (a)              (b)              (c)
```

Fig. 6. Theoretical structure of the tree-view by Component (a), Building Level (b), and Construction Zone (c).

4. Implementation of the BIM-based LPS prototype tool

The features of the tool illustrated in Fig. 5 are presented and applied to a Singapore Housing & Development Board (HDB) Carpark, which was used as a pilot project for the development of the prototype tool. The HDB Carpark comprises of eight levels with a length of 35 m and a width of 30 m. The carpark consists of a large parking area on each level, whereby the stories of one part of the structure are offset by a half floor to the stories of the other part. There is a stairway located at each end of the HDB Carpark as well as rooms for technical installation and staff on the lower floors.

The features of the tool are presented in a logical sequence in which the individual features are also implemented in a construction project. The division of work zones is presented (Section 4.1) followed by the quantity take-off, which is based on a filtering system by construction zone, building level, and building element type (Section 4.2). Next, the construction productivity factor database is introduced (Section 4.3), which serves as a basis for creating the LPS-based construction schedule. With the schedule loaded into the tool, the task data of the individual building elements can be reviewed in combination with the model information of the element (Section 4.4). The application of the LPS-based 4D construction simulation (Section 4.5) provides entirely new possibilities for the representation of construction schedules, which allows the analysis of the project in terms of constructability, logistics, missing activities, or safety issues prior to construction. Finally, another highlight feature of the tool, the short-term planning evaluation (Section 4.6) is introduced in detail.

4.1. Construction zoning

When dealing with large construction projects, which involve multiple cranes and large working areas a common way to manage the resource allocation is the division of work zones. Each work zone is usually comprised of a similar work area and is set by a horizontal grid across the workspace, meaning that all levels within the horizontal grid belong to the same zone. The number of zones is mainly dependent on the shape of the construction project and the number of cranes. Dividing the project into construction zones and assigning each zone to a unique color the objects of the 3D Model can be visualized according to its zone. While assigning the zones to the objects the tree-view (Fig. 6(c)) is updated in real time, so that the tree-view provides a clear overview of which objects have already been assigned to a zone and which objects are still pending. By deselecting the checkboxes of the tree-view individual objects and complete construction zones can be hidden in the 3D model viewport to allow the zoning selection of each individual object. The project is divided into two different construction zones, Zone 1 (blue) and Zone 2 (red) (Fig. 7). It is assumed that one crane is assigned to each construction zone.

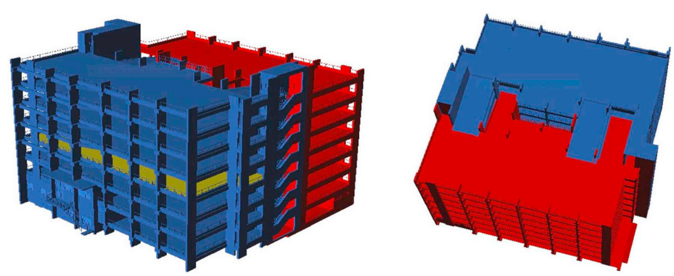
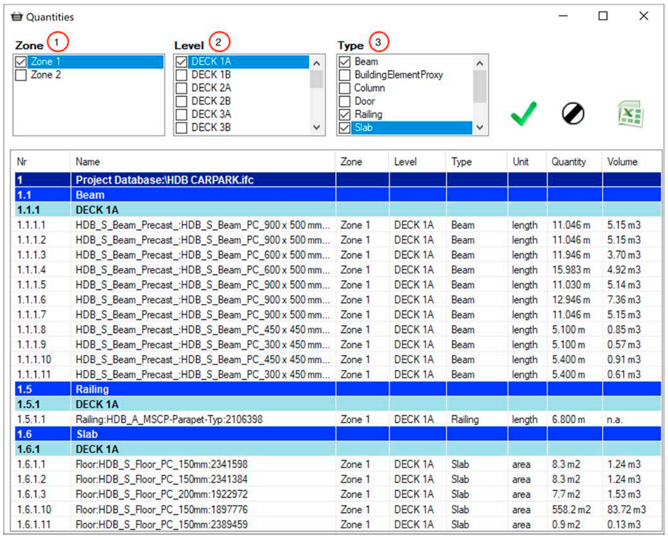


Fig. 7. 3D visualization of the model with assigned construction zones – Zone 1 (blue) and Zone 2 (red).

4.2. Quantity take-off

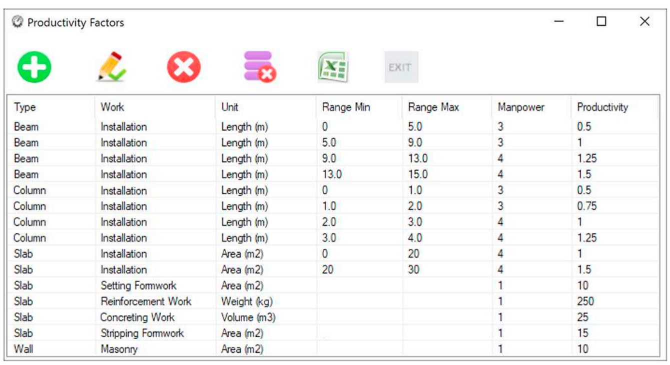
The project's construction quantities can be stored easily and retrieved from the object-related data in the BIM model. Having an accurate quantity ultimately helps to reduce waste. The developed tool simplifies the accessibility of the quantity data when compared with currently used BIM software, which often requires a complicated and time-consuming selecting of individual objects to calculate quantities. Fig. 9 gives an overview of the quantity take-off feature from the tool. In the selection menus by Zone ①, by Level ②, and by Type ③, the user can filter the quantity data accordingly to the data of interest. The filtering is particularly helpful because the user can directly differentiate between the quantities for individual building levels or types. Fig. 8 shows the quantities for the beams, railing, and slabs (Type) on level Deck 1A in Zone 1. By exporting the data to a comma-separated variable (CSV) file, which is a plain text file, and compatible with Microsoft

[1] For a description of the IFC-GUID, see: http://www.buildingsmart-tech.org/implementation/get-started/ifc-guid



Nr	Name	Zone	Level	Type	Unit	Quantity	Volume
1	Project Database:\HDB CARPARK.ifc						
1.1	Beam						
1.1.1	DECK 1A						
1.1.1.1	HDB_S_Beam_Precast_:HDB_S_Beam_PC_900 x 500 mm...	Zone 1	DECK 1A	Beam	length	11.046 m	5.15 m3
1.1.1.2	HDB_S_Beam_Precast_:HDB_S_Beam_PC_900 x 500 mm...	Zone 1	DECK 1A	Beam	length	11.046 m	5.15 m3
1.1.1.3	HDB_S_Beam_Precast_:HDB_S_Beam_PC_600 x 500 mm...	Zone 1	DECK 1A	Beam	length	11.946 m	3.70 m3
1.1.1.4	HDB_S_Beam_Precast_:HDB_S_Beam_PC_600 x 500 mm...	Zone 1	DECK 1A	Beam	length	15.983 m	4.92 m3
1.1.1.5	HDB_S_Beam_Precast_:HDB_S_Beam_PC_900 x 500 mm...	Zone 1	DECK 1A	Beam	length	11.030 m	5.14 m3
1.1.1.6	HDB_S_Beam_Precast_:HDB_S_Beam_PC_900 x 500 mm...	Zone 1	DECK 1A	Beam	length	12.946 m	7.36 m3
1.1.1.7	HDB_S_Beam_Precast_:HDB_S_Beam_PC_900 x 500 mm...	Zone 1	DECK 1A	Beam	length	11.046 m	5.15 m3
1.1.1.8	HDB_S_Beam_Precast_:HDB_S_Beam_PC_450 x 450 mm...	Zone 1	DECK 1A	Beam	length	5.100 m	0.85 m3
1.1.1.9	HDB_S_Beam_Precast_:HDB_S_Beam_PC_300 x 450 mm...	Zone 1	DECK 1A	Beam	length	5.100 m	0.57 m3
1.1.1.10	HDB_S_Beam_Precast_:HDB_S_Beam_PC_450 x 450 mm...	Zone 1	DECK 1A	Beam	length	5.400 m	0.91 m3
1.1.1.11	HDB_S_Beam_Precast_:HDB_S_Beam_PC_300 x 450 mm...	Zone 1	DECK 1A	Beam	length	5.400 m	0.61 m3
1.5	Railing						
1.5.1	DECK 1A						
1.5.1.1	Railing:HDB_A_MSCP-Parapet-Typ:2106398	Zone 1	DECK 1A	Railing	length	6.800 m	n.a.
1.6	Slab						
1.6.1	DECK 1A						
1.6.1.1	Floor:HDB_S_Floor_PC_150mm:2341598	Zone 1	DECK 1A	Slab	area	8.3 m2	1.24 m3
1.6.1.2	Floor:HDB_S_Floor_PC_150mm:2341384	Zone 1	DECK 1A	Slab	area	8.3 m2	1.24 m3
1.6.1.3	Floor:HDB_S_Floor_PC_200mm:1922972	Zone 1	DECK 1A	Slab	area	7.7 m2	1.53 m3
1.6.1.10	Floor:HDB_S_Floor_PC_150mm:1897776	Zone 1	DECK 1A	Slab	area	558.2 m2	83.72 m3
1.6.1.11	Floor:HDB_S_Floor_PC_150mm:2389459	Zone 1	DECK 1A	Slab	area	0.9 m2	0.13 m3

Fig. 8. Quantity take-off of the 3D Model – filtering of the quantities according to the construction zone, building level, and building element type.



Type	Work	Unit	Range Min	Range Max	Manpower	Productivity
Beam	Installation	Length (m)	0	5.0	3	0.5
Beam	Installation	Length (m)	5.0	9.0	3	1
Beam	Installation	Length (m)	9.0	13.0	4	1.25
Beam	Installation	Length (m)	13.0	15.0	4	1.5
Column	Installation	Length (m)	0	1.0	3	0.5
Column	Installation	Length (m)	1.0	2.0	3	0.75
Column	Installation	Length (m)	2.0	3.0	4	1
Column	Installation	Length (m)	3.0	4.0	4	1.25
Slab	Installation	Area (m2)	0	20	4	1
Slab	Installation	Area (m2)	20	30	4	1.5
Slab	Setting Formwork	Area (m2)			1	10
Slab	Reinforcement Work	Weight (kg)			1	250
Slab	Concreting Work	Volume (m3)			1	25
Slab	Stripping Formwork	Area (m2)			1	15
Wall	Masonry	Area (m2)			1	10

Fig. 9. Construction productivity factors of the various building types according to the construction method (work) and construction criteria (unit).

Excel, the project quantities can be used for further quantitative analysis in the spreadsheet.

4.3. Construction productivity factors

Construction productivity factors play an essential role in the estimation of task durations. Construction companies primarily rely on their experience from previous projects. However, the reliability of productivity factors is often weak, and during the project, the as-built construction productivity is usually not tracked or used to adjust the planning. For this reason, the tool includes a database with construction productivity factors (Fig. 9), which serves as the basis for estimating the individual task durations. Since the tool does not include a project-scheduling tool, the individual task durations were calculated in MS Excel using the exported quantities of the project (Fig. 8) and the construction productivity factors (Fig. 9).

When defining construction productivity factors, a distinction is made between tasks dealing with prefabricated elements and in-situ objects. The productivity, or rather the duration of installing prefabricated elements, is dependent on the size of the element and the availability of equipment. For this reason, a unit range of the element must be specified when defining the productivity factor of prefabricated elements. Fig. 10 shows the productivity factor of a prefabricated column element. Since the duration of the installation is greatly dependent on the length of the column, the unit criterion is set to “Length”. Accordingly, the productivity, or more accurately, the

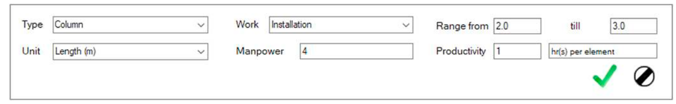


Fig. 10. Construction productivity factor for prefabricated column elements with a length range between two and three meters (construction criteria).

duration of 1.0 h per element only applies to elements within the specified length range. The manpower value describes the number of workers required to execute the task efficiently.

In contrast, the productivity of in-situ tasks is determined independently of the size of the object, and the amount of manpower. Thus, the manpower value is given as one, and the productivity is defined in “units per worker and per hour” (Fig. 9).

4.4. Object and task information

The user interface of the BIM-based LPS tool is shown in Fig. 11. The object tree-views (Fig. 6), introduced in Section 3.2 are arranged at the left-hand side and offer a detailed overview of the objects being executed in the selected week of the short-term planning phase of the LPS. By way of example, Fig. 11 shows the object tree-view by Component of the Lookahead planning week two weeks ahead of execution. As already mentioned in Section 3.2 the objects are additionally colored according to its task status.

By selecting an object in the object tree-view, the object in the 3D Model, or its corresponding task in the timeline, is highlighted. The object and task information containing the (1) Model Data, (2) Schedule Data, and (3) Productivity Data are displayed at the right-hand side of the user interface. The different windows contain the following task information:

(1) Model Data: Structural information on the construction method (prefabricated or in-situ), material specification, quantities (physical dimensions, surface area, volume, and weight) as well as further model related information about the construction zone, building level, and building type.

(2) Schedule Data: Task information on the task status (Section 1.3), constraints, as well as planned and as-built schedule and resource data.

(3) Productivity Data: For in-situ tasks, the planned task duration is calculated based on the quantities and the productivity factors (Section 4.3) for the sub-tasks setting the formwork, reinforcement work, concreting work, and stripping the formwork. The as-built productivity of the sub-tasks is calculated based on the input of the as-built quantities and durations.

Once a task is completed, the task status is set to “finished”, and the as-built task data (schedule data, resource data, and quantity) are inserted for an automatic as-built productivity calculation. The input data are stored in a MySQL database and used for an evaluation of the short-term planning. This also provides a good basis of knowledge transfer for the future short-term planning.

The tool is not only intended to be used by the project planners and engineers, but also by the last planners on site. This is to ensure that all relevant information makes its way to the onsite personnel, and as-built task data are directly captured from the responsible personnel on site. Commercial software, such as Autodesk Navisworks and Synchro provide the opportunity to bring the information to the personnel performing the tasks on handheld tablet PCs by using software add-ins such as BIM 360 Field in the case of Autodesk Navisworks. Because all data are cloud-based, an extension of the tool is also conceivable, so that the data can be entered in the field by creating an interface for mobile tools. However, tablets or other mobile devices are not very useful yet, as they have a limitation when rendering full 3D images. Also, their graphics rendering

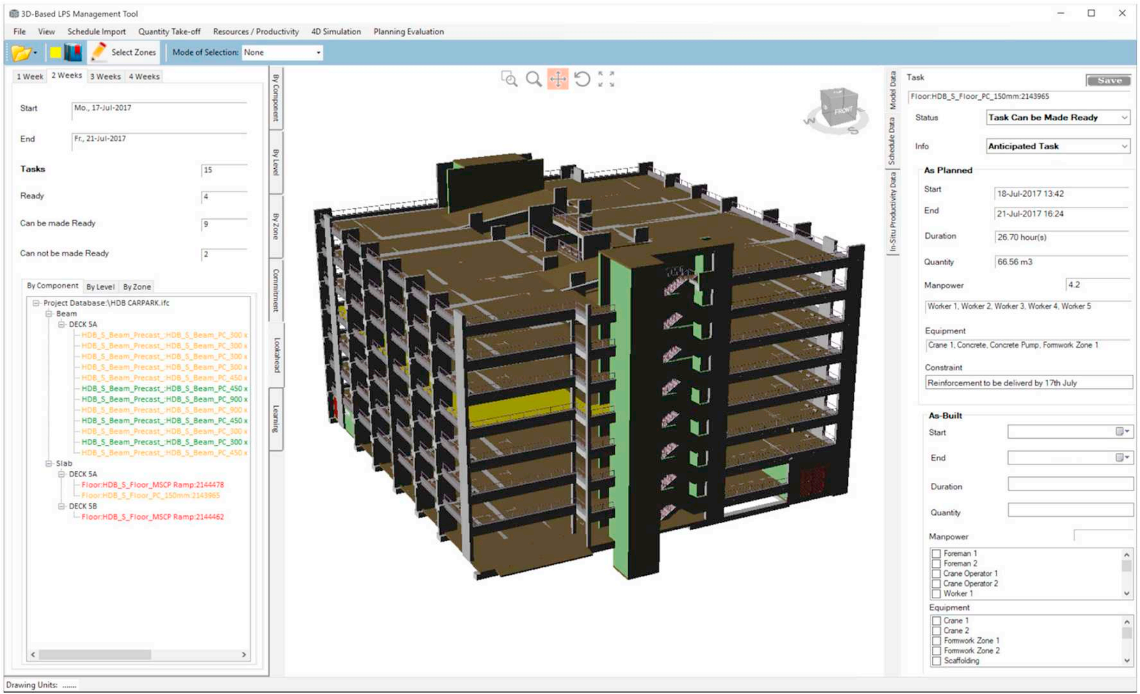


Fig. 11. User interface of the tool showing the object tree-view, the visualization of the 3D model, and the object & task information window.

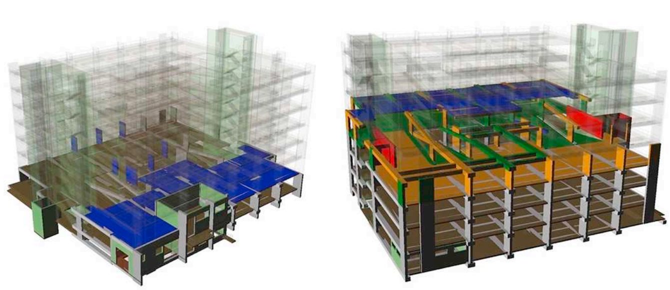
speed is not up to the same level or as powerful as the one available in desktops/laptops. However, the future possibilities of mobile applications are great, especially cloud-based ones.

4.5. 4D construction simulation

3D Models can be used extensively as a visualization and communication tool since the utilization of 4D visualization allows a more intuitive comprehension of the construction process than traditional 2D drawings and separate schedule information [14]. The tool provides two different simulation methods – "Learning" and "Short-term Plan" – to run the 4D construction simulation.

The simulation method "Learning" simulates the as-built construction progress from the beginning of the project up to the current stage of the project by retrieving the as-built data from a MySQL database. An example of a "Learning" simulation is shown in Fig. 12(a). Objects that are transparent are not constructed yet, objects that are currently under construction are highlighted in blue and objects that have already been constructed are shown in the color assigned to the building element (in the case of the concrete elements in Fig. 12, solid grey).

The simulation method "Short-term Plan" (Fig. 12(b)) starts the simulation at the current stage of the project and simulates the scheduled tasks of the Commitment Plan and the Lookahead Plan up to four weeks ahead of construction ("rocks/processes"-level of planning detail



(a) (b)

Fig. 12. 4D visualization of the Learning construction progress (a) and Short-term planning construction process (b).

(Fig. 2)). During the time the task is under construction, the objects are also colored in blue. Afterward, the color changes to green, orange or red according to the planning status of the task (i.e., completed tasks (original color assigned to building element), tasks currently under construction (blue), tasks ready (green), tasks that can be made ready (orange), and tasks that cannot be made ready (red)).

The different coloring of the objects based on their task status is particularly helpful for the short-term planning process. Tasks that are not ready for execution are immediately clear. In addition, the effects on the future planning as well as the resulting disruptions and delays can be visualized and analyzed.

4.6. Construction planning evaluation

In order to cover the Learning phase well – which is a significant part of the LPS – and support the principle of continuous improvement, streamlining work, and reducing waste in the form of cost, time, and rework, the project planning is evaluated in terms of productivity, manpower allocation, and quantification of waste. As indicated in Section 1.4 the most widely used tool to promote continuous improvement is the four-step PDCA-cycle (Fig. 3). Based on the evaluation tools described below, the methodology of the PDCA-cycle can be applied on a weekly basis in order to improve the planning reliability, reduce the amount of waste, and improve quality and customer satisfaction.

4.6.1. Productivity planning evaluation

The evaluation of the construction productivity focuses on the comparison of the planned duration with the as-built duration for prefabricated objects (Fig. 13) and the planned productivity with the as-built productivity for in-situ objects (Fig. 14). By determining the daily variance of the planned value with the average as-built value, the concept to continuously improve the planning performance is addressed. The productivity planning can be evaluated for all types of building components for which a construction productivity factor has been defined. By way of example, Fig. 13 shows the duration evaluation of prefabricated column elements of a unit length between two and three meters. The diagram shows that the as-built duration of virtually

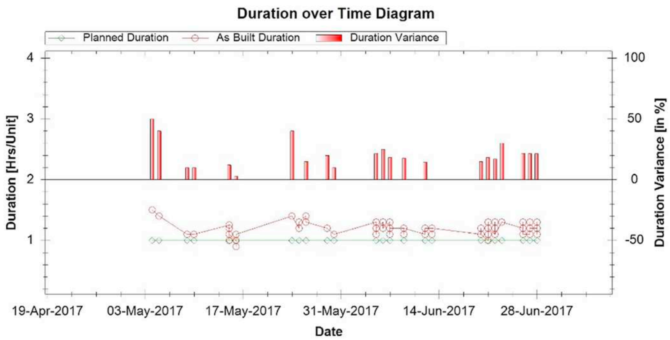


Fig. 13. Evaluation of the planned vs. as-built duration of prefabricated column elements with an element length between two and three meters.

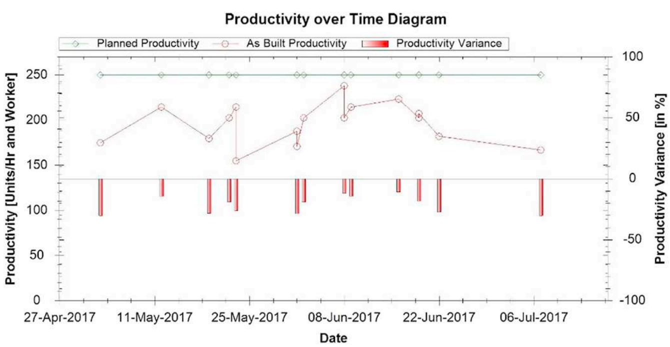


Fig. 14. Evaluation of the planned vs. as-built productivity of reinforcing slab elements.

all elements within the selected length range was greater than the planned duration of one hour.

Contrary to Fig. 13, which shows the evaluation of prefabricated elements, Fig. 14 depicts the productivity evaluation of reinforcing in-situ slab elements. Again, the variance shows a very high deviation to the value of the planned productivity factor, which results from the low as-built productivity of reinforcing slab elements. It is also possible to illustrate the evaluation of further in-situ tasks, for example, setting the formwork, concreting works, and stripping the formwork.

The diagrams provide a good basis to apply the PDCA-cycle, in particular, the steps "Check" and "Act". Both diagrams show an enormous potential of planning improvement, which will result in the variance tending towards zero during the following weeks of construction. This is achieved by adjusting the planned duration/productivity of the tasks in the Lookahead planning process. However, the causes for the high as-built duration and the low as-built productivity must also be examined – workers per area, logistical problems, or skills of workers – and, if necessary, adjustments need to be made in order to reduce the variance of future tasks.

4.6.2. Manpower allocation planning evaluation

Besides an optimized productivity planning, the share of non-value added activities also can be reduced by optimizing the manpower assigned to the individual tasks. The manpower allocation also can be evaluated for all types of building components for which a productivity factor has been defined. By comparing the average as-built productivity of a specific manpower to its average planned productivity of the same manpower, while also showing the frequency of occurrence of the as-built and the planned manpower, multiple findings can be obtained (Fig. 15):

a. The most frequently used as-built manpower deviated from the most frequently used planned manpower
b. The shortest average as-built task duration is achieved with a manpower unit of three

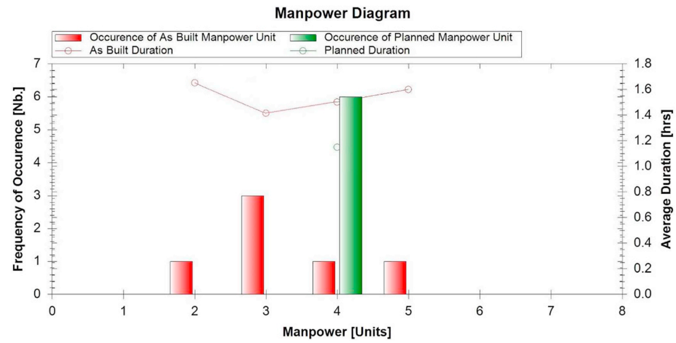


Fig. 15. Evaluation of the planned vs. as-built manpower of prefabricated column elements with an element length between two and three meters.

Accordingly, the illustration of the correlation between the as-built manpower and the duration in Fig. 15 allows the planner to adjust the manpower resources to the optimal amount corresponding to the shortest duration and thereby eliminating the non-value-adding manpower resources. The evaluation of the manpower allocation planning as, well as of the production planning, can be implemented by applying the principle of continuous improvement. The most widely used tool to establish continuous improvement is the PDCA-cycle, which is an ongoing effort to improve the reliability of project planning as well as the overall productivity and efficiency of construction projects. The efforts of the continuous improvement process usually seek incremental improvements over time by continually evaluating and improving processes in the light of their efficiency and effectiveness.

4.6.3. Quantification and evaluation of waste

To have an understanding of the amount of the waste quantities and to reduce the share of non-value added materials, the waste quantities are represented in time diagrams, such as shown in Fig. 16. At the same time, the project manager receives a very detailed overview of the quantities already installed in the project. The waste can be evaluated for materials such as concrete or reinforcement and, just as the evaluation of the productivity and the manpower allocation, the evaluation is based on the types of building components. Once the status of a given task (Fig. 11) is set to "task finished", the planned quantity and the as-built quantity of the respective element is considered for the quantification of waste. The as-built quantities are based on the information obtained from the construction site, for example through delivery notes, and are, as described in Section 4.4, entered manually in Fig. 11. By way of example, Fig. 16 compares the planned concrete quantities of slab elements with respect to the as-built quantities, and calculates the waste quantity based on the difference between them.

On the basis of Fig. 16, it can be determined which building component and material has the largest amount of waste material.

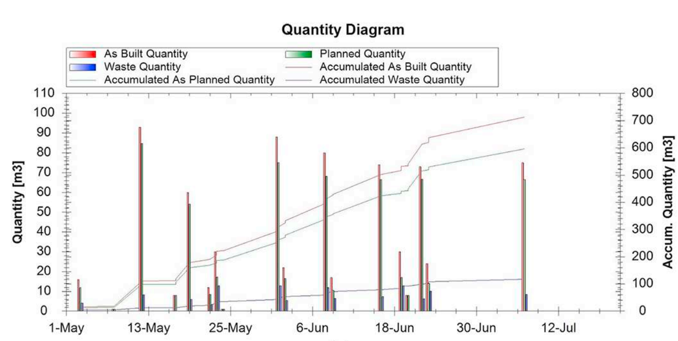


Fig. 16. Evaluation of the planned vs. as-built concrete quantities for slab elements.

Accordingly, the types with the highest amount of waste can be examined and the causes identified in order to reduce the amount of waste for future elements.

5. Conclusion

The productivity of the AEC industry has experienced a slow growth for several decades. In the last 50 years, productivity has dropped by almost 20% [28]. Some reasons include an insufficient knowledge transfer from project to project, the lack of realistic site information, and a weak short-term planning and work plans. The development of BIM and other technologies, such as augmented reality, drones, and advanced building materials, which have all reached market maturity, has vast potential for improving productivity and efficiency in the AEC industry. To utilize the enormous potential a committed and collaborative effort will be required by the whole industry [28].

This study shows that, when combining Lean Construction practices with BIM, a collaborative environment that genuinely minimizes both tangible and intangible wastes in a construction project can be created. This helps to promote an informed use of BIM and a more efficient transformation, flow, and value generation for the different project participants. Though several attempts have been made to adopt the management approach of Lean in the construction process, its full benefits have not been realized due to the nature of construction projects. In a traditional construction process, the project is divided into smaller activities, which does not support the implementation of Lean in an efficient manner. The implementation of BIM can resolve this issue by getting all the professionals involved in the project to participate early and treat the entire project as one process. BIM also provides the opportunity for an improved analysis and control of time-dependent spatial conflicts through 4D construction progress simulation, which results in a more efficient execution and is of crucial importance especially with respect to large construction sites where several contractors work on a project.

This paper presents a BIM-based LPS tool as a prototype to prove the concept of the interaction of Lean Construction and BIM. While it is recognized that the tool developed is meant as a proof of concept, and not ready yet for the industry, this does not mean that the idea shown cannot be made ready. The prototype development is mature and enables integrated Lean Construction management with the use of 3D construction models. Although this could be seen as a limitation, it also opens the opportunity for future research. Looking at the next steps, some features could be implemented. For example, an integrated project scheduling tool would automate the entry of task durations in the scheduling software (e.g., MS Project), that is estimated automatically in the LPS tool by means of the construction productivity factors. Also, the tool needs to be made available for IFC files created from software other than Revit by using the IFC-GUID for automatic linking of the 3D model and the schedule. In addition, the implementation of the key indicators (Tasks Anticipated, Tasks Made Ready, and especially Percent Plan Complete), which serve as key indicators to control the continuous improvement process in the short-term planning are an important step to better monitor the learning curve of short-term planning. Further research and more hands-on experience needs to be gained in mobile applications and rendering of 3D models on tablets or other mobile devices as this area has vast potential to reduce waste, especially in the form of duplication of work, to promote the knowledge transfer within a project, as well as from project to project, and to increase the reliability of short-term construction planning.

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