BIMsite – Towards a BIM-based Generation and Evaluation of Realization Variants Comprising Construction Methods, Site Layouts and Schedules

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Abstract. Despite the proliferation of BIM tools in construction process planning, the BIM-based development of a digital representation of the construction phase, including detailed site layout plans, is still in a very early phase. Most planners still use manual methods and rely on experience when it comes to the selection of construction methods and site layout planning. The following paper introduces BIMsite, a recently started research project, focussing on BIM-based site layout planning under the consideration of different construction methods. The project investigates how to generate different variants of construction site layouts based on different construction methods in a semi-automated way; and how to evaluate those variants utilizing construction simulation approaches. The paper provides an overview of the initial research, focussing on first approaches regarding construction site generation, optimization and simulation.

1. Introduction

Until recently, building layouts and construction drawings have been designed and delivered in 2D, leading to problems and delays on the construction site due to insufficient depth of planning. Building Information Modeling (BIM), the digital representation of physical and functional characteristics of a building, has been introduced into the field of civil engineering to improve planning efficiency and planning quality (Eastman et al., 2011; Borrmann et al., 2015). BIM facilitates and accelerates the planning process by the use of semantic construction components and continuous data exchange. However, concerning the selection of construction methods on one hand and planning of construction work and construction schedules on the other hand, most engineers still use manual methods and rely on experience. Up to now, the development of a representation of the construction process in BIM is still in an early phase, giving away the opportunity to optimize the planning process towards time efficiency, robustness, as well as health and safety concerns.

The recently started project BIMsite is focused on the transition from construction planning to construction process. A tool is created to assist engineers during the planning process: different construction variants and materials, as well as the setup of building site facilities are automatically generated, and the construction sequences are simulated. By this means, decisions are supported by extensive evaluation of the costs, robustness and duration of the building process. For example, concrete elements can be constructed using precast concrete components or in-situ concrete, leading to complex influences on costs and duration: Using precast concrete, high-power cranes and longer travel journeys may be necessary; using in-situ concrete, additional storage locations for formwork and reinforcement steel as well as extended curing times have to be taken into account. Up to now, these influences are not considered adequately during the selection of different construction methods and haven't to the best of our knowledge, been part of former research.

BIMsite aims at an early, comprehensive variant analysis with as little user interaction as possible. For the semi-automated generation of a set of site layout plans, a layout generator, which is able to extract as much information from the building information model as possible, will be developed. The project utilizes the Industry Foundation Classes (IFC), an open file format specification used to digitally describe building data. The project comprises three succeeding main steps: “model preparation and simulation”, “analysis and evaluation”, and “monitoring” (Figure 1).

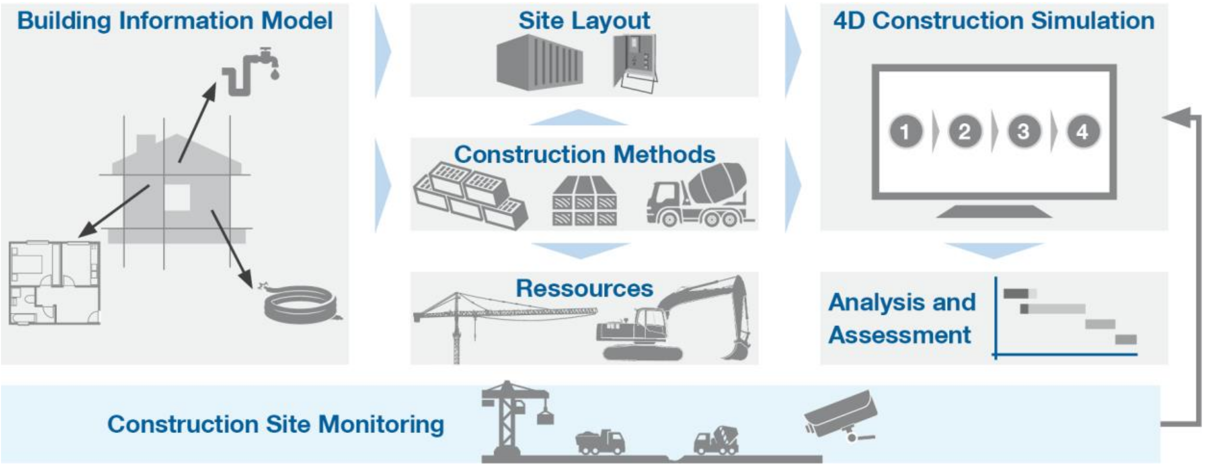

Figure 1:BIMsite – Project Overview

During model preparation and simulation, BIM models are examined for missing and corrupt information; possible ways to integrate required information a-posteriori are identified. The reproduction of construction sequences and building site facilities within a BIM model, as well as commonly used resources are investigated and implemented. Following this, a methodology for a construction sequence simulation is developed. The second step of the project includes the development of systematic evaluation methods to analyze and evaluate the generated building site facility and construction sequence plans. Different design variations are generated and weighed to assist the decision making. During the last step, the developed methods are verified and parameters are calibrated. The construction sequence plans should be robust towards unexpected changes in circumstances Finally, a pilot construction site is being chosen during the planning phase to verify the developed methods and solutions in collaboration with construction companies. One construction site layout plan is selected, and a construction sequence plan is simulated. The construction process is monitored to validate the assumptions. To evaluate the acceptance of the proposed methods, the construction companies are interviewed and suggestions for improvements are requested.

This paper presents a brief overview of selected research topics in the context of BIMsite. In the first part of the paper, it is discussed how building information models will be used within the project context. Furthermore, a brief overview of construction site modeling is given, and process patterns as well as the representation of construction procedures are introduced. The second part of the paper describes boundary conditions of site layouts and discusses different site layout optimization approaches. In the third part of the paper, the simulation of construction sites is discussed and the development of a key performance indicator system is described. Finally, a short summary is given and the further line of research is described.

2. Building Information Models and Construction Site Modeling

Construction site layouts strongly depend on the building itself and the used construction methods. The dimension and position of needed storage areas and corresponding transport ways for instance strongly depend on the geometry of the building and resources such as materials and machinery needed for construction. In conjunction with construction method models, building information models have the potential to serve as a basis for automated site layout planning. The amount of material needed for certain building elements, for example, can be derived from building information models using quantity take-off techniques (Monteiro & Poças Martins, 2013). Therefore, the modeling of computer interpretable construction method models, as well as the question how they can be utilized for automated site layout planning and simulation, form a vital part of the planned research. Furthermore, it will be investigated which kind of information is necessary in building information models to derive the construction methods that can be applied to building sections and elements like walls or slabs automatically or semi-automatically.

Building information models can be defined at different Levels of Development (LOD). The LOD specifies content and reliability of a model. BIMforum (2015) for example specifies six LODs reaching from conceptual information that must be considered approximate on the lowest level, up to more detailed and reliable information on higher levels. Typically, the models of earlier design phases are of lower LODs and therefore do not specify construction details. However, in order to enable an analysis of different construction methods and how they might affect the construction site layout, it will be addressed how models of lower detail and reliability can be used to derive the construction methods that can be applied to building sections and elements like walls or slabs (semi-)automatically. The resulting concept will be integrated into a demonstrator working with IFC-files. Requirements on IFC-files can be specified in a Model View Definition (MVD), which defines a schema that must be satisfied by valid files (buildingSMART International Ltd., 2016). Therefore, a model checker based on a proposed Model View Definition (MVD) will also be part of the resulting prototype. It will be used to validate and check if the building information models provide the information needed for automated site layout planning.

One way of modeling construction methods in a 4D environment (3D + time) is within the scope of pattern based approaches such as proposed by Wu et al. (2010), König et al. (2012) and Benevolenskiy et al. (2012). According to them, a construction pattern is a reusable concept that can be applied or assigned to certain building elements. The pattern defines and models sub-processes and their general set-up like the required workforce, machinery, material and time in order to build the component. For instance, a construction method for in situ concrete columns could be applied to columns in an IFC model by assigning the corresponding pattern. The pattern then determines the needed sub-processes like erecting formwork, installing reinforcement, placing the in-situ concrete, curing the concrete and finally stripping the formwork as well as needed resources. Furthermore, process patterns can be modeled in a hierarchical way which allows the abstraction from single building elements to compositions of elements like rooms, stories or on top-level entire buildings as demonstrated by Wu et al. (2010). Thus adequate process patterns can also be applied to coarse grained building information models of early planning phases. Furthermore, they are a promising approach for the mostly automatic generation of site layout plans and construction schedules based on models not reaching for higher LODs. The assignment of different matching process patterns, defining different construction methods, will allow for an analysis of different construction methods in early planning phases with minimal effort and is therefore an essential component of BIMsite. Consequently, methods of how to extend and combine former pattern based approaches of modeling construction methods will be investigated. Since BIMsite aims to assess site layouts in terms of safety and productivity the formalized construction method models must consequently reflect both aspects.

A characteristic site layout feature, affecting safety as well as productivity, is space. Looking at a snapshot of a large construction site, one will typically notice many construction processes taking place simultaneously. And as each process requires space, spatial conflicts may occur. Either in terms of congestion, like one tower crane operation is blocking another tower crane and thus affecting the overall productivity, or as safety hazard, like construction workers operating directly below suspended crane loads. Akinci et al. (2002) proposed a model that allows the detection of spatial conflicts and their classification regarding type and severity which could serve as a basis of automatic scheduling while avoiding spatial conflicts. Marx et al. (2010) integrated a subset of this model into a discrete event simulation limited to the detection of spatial conflicts between simultaneously operating tower cranes in order to generate optimized schedules. Later they proposed an approach where spatial requirements are implemented alongside process patterns that can be applied to building elements like *IfcWall* components and can be integrated into simulation models as soft constraints in Constraint Based Discrete Event Simulation. However, the rating of severity and the type of spatial conflicts is only implied vaguely (Marx & König, 2013). A more recent approach from Zhang et al. (2015) introduced a more detailed workspace model that integrates into the BIM-IFC world, but focuses mainly on safety. Based on a detailed state-of-the art research and discussion with industry partners, we will combine and refine existing approaches of workspace modeling and will propose a model that can serve as a basis for site-layout planning and site layout simulation. In this regard we will focus on the BIM-based automatic assignment of spatial requirements of construction processes to building elements as well as on general requirements of simulation-based construction site safety and productivity analysis (see section 3).

Both, automated site layout planning and construction simulation depend on models that determine the build order of certain building parts. Most obviously, before the construction process of a slab can be started, the subjacent supporting columns or walls have to be load bearing. The manual scheduling of the corresponding processes is potentially a time consuming task, especially when it comes to large buildings. However, predecessor-successor-relationships can be derived from building information models by applying corresponding rules or templates. In order to do so spatial query languages can be utilized (König et al., 2012). In order to support planners, it will be investigated how query languages like *QL4BIM* (Daum & Borrmann, 2014) and building information models can be used to support the definition of more sophisticated predecessor-successor-relationships.

3. Semi-Automated Generation and Optimization of Site Layouts

For generating the site layouts, external circumstances and boundary conditions are investigated and combined with requirements on facilities to formulate and solve an optimization problem. Different alternative construction methods will lead to site layout variants, which will serve as a basis for site layout simulation and variant evaluation in section 4.

3.1 Boundary Conditions for Site Layout Planning

As an input for the layout problem information about the types of facilities to be placed and the quantity of each facility type and/or the size of each facility is necessary. To generate this information, data about the building geometry, the applied construction methods as well as the time schedule will be extracted from the BIM model.

Tower cranes play a key role in building construction projects. One method of calculating the number of tower cranes is given in Equation (1), in which N_c represents the number of cranes, V the gross volume and C the crane capacity (Schach & Otto 2008, Hofstadler 2007). Reference values for crane capacities depending on the construction method can be found in (Schach & Otto, 2008). M is the time period measured in months, for which the usage of one or more cranes is scheduled. Once the number of cranes is determined, specific tower cranes will be selected using the digital tower crane deployment planner by (Frenz et al., 2014). Their approach is based on providing applicable crane models based on a set of input parameters, such as boom length and lifting capacity for the upper structure. In addition, a 3D-model of the crane with the selected characteristics will be generated automatically using pre-defined construction components.

$$N_c = \frac{V}{C \cdot M} \tag{1}$$

The number of office containers, washrooms and day accommodation strongly depends on the number of site personnel, which can be approximated for building construction projects by Equation (2), in which n represents the number of site personnel and V the gross volume. A stands for the effort necessary for certain tasks, e.g. the masoning of walls, and is measured in hours per unit of quantity (m, m^2 or m^3). T is the total construction time measured in days and t_{AT} are the daily working hours (Berner et al., 2013).

$$n = \frac{V \cdot A}{T \cdot t_{AT}} \tag{2}$$

The necessity and the size of a concrete pump, a concrete mixer and/ or a mortar mixer as well as the size of storage area depend on the construction method. Suggestions for dimensioning are given in (Schach & Otto, 2008). The width of the construction road depends on the engaged construction machines.

In addition to the type, number and size of facilities, restrictions need to be considered for the generation of a layout. These include geometric constraints, e.g. facilities must be placed inside the construction site boundaries and outside of the building space. Other restrictions concern safety aspects, for instance cranes should not lift their loads above office containers, or ground characteristics, e.g. load-bearing capacities must be considered when placing a crane. All constraints will be categorized in either hard constraints (mandatory requirements) or soft constraints (recommendations).

3.2 Generation and Optimization of Site Layout Variants

Commonly, it is up to the planner to decide between different construction methods to realize a construction project. Different construction methods entail different materials, storage spaces, construction equipment and process patterns, leading to overly complex cost and time distribution. To facilitate the process of selecting particular construction methods based on distinct, comparable criteria, different methods are examined.

Depending on the construction methods, the building process can be divided into discrete construction stages according to the construction progress. Each construction stage has different requirements on facilities – some facilities may not be necessary in every construction phase. Therefore, a dynamic site layout model is required. Through varying the site layout plan over the duration of the construction process, optimal layouts can be realized for all construction stages. In the beginning of each construction stage, facilities that are not needed any more are dismantled and may be replaced by other facilities. The number of construction stages and, consequentially, facility alterations, has to be thoroughly pondered: too few construction stages may lead to suboptimal exploitation of the building site, too many construction stages and modifications lead to disorganized and confusing site structures (Kumar & Cheng, 2015).

Correspondingly to the variation of facilities, space requirements and constraints vary over the construction stages. Building site areas are redefined in each stage, leading to a complex layout system. Solely based on the experience of planners, optimal solutions are hardly found. However, taking into account the constraints specified in 3.1, an optimization problem can be formulated to evaluate different layouts. The optimization of the site layout implies the minimization of an objective function with multiple conflicting objectives (Yahya & Saka, 2014). Typical objectives are the reduction of costs and the increase of safety. To measure the costs, which arise on a building site, different parameters are used: A strong indicator of efficiency are the travel distances and frequencies between different facilities to calculate the cost for transportation of materials and workers' travel paths. Setup, dismantling and relocation of facilities on the building site produce additional costs. Khalafallah & El-Rayes (2011) include costs for wildlife control and debris control systems. To minimize the objective function of the optimization problem, various optimization algorithms have been used: Huang & Wong (2015) implement a binary-mixed-integer-linear program, which is solved using a standard branch-and-bound algorithm in a commercial software. Shawki et al. (2010) and Kumar & Cheng (2015) use genetic algorithms for layout creation, starting with random layouts which are crossed and mutated. Several researchers use artificial intelligence to solve the optimization problem. Research includes swarm intelligence based meta heuristic algorithms, implemented by Yahya & Saka (2014) by using an artificial bee colony algorithm and Ning et al. (2010) by using a max-min ant system. Yeh (1995) uses annealed Hopfield neural networks. Another approach, as used by Andayesh & Sadeghpour (2013), uses the theory of minimal total potential energy, moving objects until they reach the equilibrium state. To decide on a suitable and efficient optimization approach, further literature research has to be conducted to analyze advantages and disadvantages of the different approaches.

4. Simulation and Evaluation

As generated variants of site layouts need to be evaluable and comparable, the valuation basis of those variants is central to the research within BIMsite. Therefore, a key performance indicator (KPI) system will be developed with an emphasis on occupational safety and productivity aspects. The calculation of those KPIs will utilize a construction simulation approach that incorporates the model of the formerly defined site layout and thereby induced constraints.

4.1 Simulation

Within the scope of the BIMsite project an approach for construction simulation with an emphasis on site layout evaluation will be developed. A promising and widespread approach is the so called constraint based discrete event simulation (DES) (Beißert et al., 2007). It has been shown, that constraint based DES is applicable to the evaluation of several aspects relevant to site layout evaluation and allows inter alia for simulation models considering available resources such as machinery, available workforce, skills, material and construction processes (König et al., 2012). Furthermore constraint based DES can be used to analyze resource utilization on construction sites in order to identify bottlenecks induced by logistic chains (König et al., 2011). Additionally, the approach of Beißert et al. has been extended by spatial constraints in order to detect and avoid spatial conflicts between tower cranes (Marx et al., 2010) and workspaces in general (Marx & König, 2013). Moreover, discrete event simulation can also be utilized for process schedule optimization (Bügler et al., 2013). Based on the refinement and adaptation of prior research in constraint based event simulation a simulation model will be developed, that explicitly takes the construction site model into account and allows for an extensive construction site simulation. The simulation model will further respect the location where construction processes take place and therefore, in conjunction with building information models and detailed construction process information enable the evaluation of logistic chains and spatial conflicts which will serve as a basis for safety and productivity evaluation.

An advantage of using constraint based DES is that at each event, the simulation engine identifies the processes that can be started by checking the constraints the simulation model has been initially fed with. This reduces the effort regarding input data preparation since no hard coded detailed schedule information needs to be created. Furthermore the approach can be extended by differentiating hard constraints that have to be fulfilled and soft constraints that influence the selection of upcoming processes which allows for the application of more detailed strategies during the simulation process (Beißert et al., 2010). However, the preparation of constraints still remains a potentially time-consuming task, which has been addressed by former research. The utilization of process patterns can reduce the effort needed for data preparation and helps to mitigate repetitive user input (Marx & König, 2011). Since BIMsite aims at the generation and simulation of several site layout variants the development of innovative concepts for automatized generation of simulation input data will also be part of our research. In this context possibilities of how to assign process patterns to building parts based on building information models will be investigated (see section 2).

4.2 Evaluation: Key Performance Indicator (KPI) System

During the simulation a lot of data about the building process is being generated. To evaluate this data, which strongly depends on the applied construction methods and the generated site layout plan, a KPI system will be developed. The emphasis is placed on measuring occupational safety and productivity aspects.

Safety remains a big issue in the construction industry due to high accident and fatality rates (Zhang, Sulankivi, et al., 2015). In the BIMsite project two different aspects of occupational safety will be regarded: Firstly safety related to the applied construction methods and secondly safety related to the positioning of facilities. This involves identifying and quantifying potential risks at different stages of construction considering interactions between the building and workers, the building and facilities, facilities and workers and facilities among themselves.

While safety aspects might influence the reputation of the construction company, keeping a high productivity level is a necessary prerequisite for the financial success of a company. Potential KPIs to measure the productivity are total construction time, utilization rate of construction machines and robustness of the construction schedule. The latter is an indicator for the sensitivity of project objectives to uncertainties such as weather conditions, machine breakdowns or delivery dates and can be measured by the deviation of realized and planned activity start time combined with the deviation of realized and planned order of activities (König, 2011).

5. Conclusion and Outlook

Building Information Modeling is able to facilitate and accelerate the planning process of constructions. However, none of the existing approaches facilitates the analysis of different construction methods and their effects on site layout planning. In this paper, an overview of the recently started BIMsite project is given. Within the project a decision support system for the planning process is developed to analyze construction processes and construction variants with regard to productivity, safety and robustness using a BIM-based approach.

In the paper, necessary properties of the BIM-model are discussed. Furthermore, the concept of process patterns for integrating construction methods as well as approaches for the automatic assignment of spatial requirements are introduced. It is discussed how the information from the BIM-model will be used to generate input parameters and constraints for the mathematical layout optimization problem. Approaches for solving the optimization problem are presented in a brief review. Next, it is examined how generated, optimized site layouts serve as an input for construction simulation. Different simulation approaches as well as key performance indicators for the variant analysis are discussed.

In future research, the presented approaches will be refined and extended. Additionally, methods enabling the validation of the approaches will be developed. These will be used on a pilot construction site, comparing the results from the simulation to parameters from the real process.

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