Semi-automated site equipment selection and configuration through formal knowledge representation and inference

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Abstract

The selection and configuration of site equipment is a fundamental part of construction preparation. Suitable site equipment supports the timely, cost-efficient and qualitative execution of the construction process. The use of planning tools based on formal knowledge management methods can both speed up the process of construction site planning and lead to better results. In this paper, we propose a rule-based knowledge inference system to support site equipment planners in a semi-automated manner using input data from building information models and working schedules. The knowledge-based system is built using the business rule management system *Drools*. Using a sample construction site, the feasibility of the proposed approach has been proven.

Keywords:
construction site equipment, building information modelling, knowledge based engineering

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1. Introduction

Inappropriately selected construction site equipment (SE) can slow down the construction process, generate unnecessary costs and constitute actual safety risks, making the process of equipment selection an indispensable step

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in execution planning. The purpose of the SE to ensure an orderly, productive and safe execution of all tasks necessary during the construction, reconstruction or demolition of a building or structure. The selection and generation of the SE provides the basis for performing the construction site layout planning (CLSP).

Site layouts are especially relevant during shell construction, as most heavy equipment is used in this phase. A prerequisite for creating reasonable site layout plans is to identify all needed SE and to determine the necessary dimensions of each element of the SE. To generate a site layout plan, the SE and layout have to be placed in the available areas.

The necessary SE varies widely depending on the conditions of the specific construction project. Due to the large deviations in the circumstances and specific requirements of construction projects, the SE has to be selected and configured individually for each project. However, according to current literature, despite the large impact of the SE on the on-site overheads and productivity of the construction, the site planning process has not been well formalized [1, 2]. Usually, planners conduct both the selection of the SE and the CSLP manually, without technological support. Oral conversation with practitioners confirmed this observation [3, 4].

The dimensioning of the individual elements of the SE is mostly realized based on the experience of the planners and rules of thumb, without qualitative or quantitative reviews. The results of the manual SE selection and CSLP planning thus depend solely on the expert knowledge and practical experience of the executing planner.

A large set of information, which is traditionally acquired in very late planning stages, has to be considered during the CSLP process, and changes in the construction design and construction methods usually require the adjustment or re-planning of the SE. To reduce the planning efforts and prevent repetitive re-planning phases, the CSLP is usually conducted only after decisions on the design and construction are final, depriving the possibility to include information about the necessary SE in the process. In this way, potentially expensive and inconvenient solutions might be condoned because the SE was not taken into account during the design phase.

To be able to include aspects of the SE selection in the planning considerations, a fast and easy way to support planners in their decisions by partly or even completely automating the planning of the construction site is necessary. This becomes even more relevant as numerous regulations and guidelines for SE selection exist. To support the planners during the generation of individual site facilities, knowledge-based systems (KBS) form a very suitable basis. These systems are computer programs that formalize human knowledge in a strict, logical and computable manner, allowing them to infer conclusions from given facts. They are used to assisting humans in solving complex problems and tasks.

KBS have been chosen for the problem at hand, as they allow the direct representation of the rules stipulated by the aforementioned regulations and guidelines. On the contrary, alternative technologies, such as case-based reasoning or machine learning, rely on the implicit derivation of knowledge from provided examples. They require a large set of training data and a human-assisted training phase. As, however, rules on SE selection are made available explicitly through textbooks, guidelines etc., a KBS approach seems to be more promising and is investigated in this paper.

This paper presents rule-based knowledge inference systems to perform the SE selection process in a semi-automated manner using input data from building information models and working schedules. In the first part of the paper, we concentrate on the fundamentals of SE planning and KBS and give an overview of the related work. In the second part of the paper, we present a system for semi-automated SE selection and generation. In the third part of the paper, we formulate rules applying to SE selection and generation, followed by the implementation of a prototype. Finally, we present a case study and conclude the paper.

2. Background

Up to now, construction site equipment is generally selected and configured by hand. However, there has been effort by several research groups to automate the planning process. In the next sections, a short overview over the traditionally SE planning and the state of the art in computer-aided SE planning is given.

2.1. Fundamentals of SE planning

The SE on construction sites is used to prepare and conduct all individual construction processes in the best possible way in order to enable a fluent and continuous construction progress. The construction SE includes all producing and non-producing facilities required on site for the construction or renovation of a structure [5].

With the construction method applied, the conditions on site, neighbouring properties and local characteristics, the boundary conditions and requirements for the construction site facilities vary from construction project to construction project. These boundary conditions cause deviations in the required material, storage spaces, construction machines and processes, so that the planning has to be conducted for each new project. Changes to the construction project or the construction process must also be followed by repeated calculations and planning, which requires extra effort. The SE can be classified into seven basic groups (see [2] and [6]).

1. Construction machinery (e.g. hoists, concrete pumps, movable machinary)
2. Social and office facilities (e.g. office and sanitary containers)
3. Storage areas (e.g. tool sheds, outside and inside storage)
4. Traffic areas, transport routes (construction roads, entrances and exits)
5. Media supply and disposal (e.g. power and water supply, waste disposal)
6. Site security (e.g. fences, illumination, scaffolding)
7. Excavation support

Different groups of SE entail different degrees of freedom concerning the planning task. While the media supply, site security and excavation support are highly restricted by the circumstances on site, the construction machinery, social facilities and storage areas are more variable. With ongoing progress, the requirements and conditions at the construction site change. The construction process is typically divided into several construction stages, where some facilities may not be required in each construction stage. Therefore, a dynamic construction site plan is required. At the beginning of each construction stage, items that are no longer needed are disassembled and replaced by other facilities [7].

Depending on the state in which a construction project is to be carried out, different laws and regulations have to be applied. This work is primarily concerned with legislation in Germany. Construction-related regulations can be found, for example, in the workplace ordinance [8] and various ISO and DIN standards (e.g. DIN 4124 [9] for excavations, ISO 668 [10] for containers, and DIN 30734 [11] for interchangeable silos.)

During the planning process, all needed SE is identified, dimensioned, and finally placed on the construction site. Following this consideration, we split the SE planning into three interdependent tasks: identification, dimensioning, and placement of the SE (Figure 1). In this paper, we seek to support the planner in the first two steps, the identification and dimensioning of necessary SE. The placement process will be subject of future publications.

The required SE can be identified explicitly—e.g. the planner demands the use of a concrete pump—or implicitly—e.g. if a concrete pump is demanded, most likely a tower crane is required to place formwork. In this paper, we propose connecting BIM models with detailed working schedules, where a construction method is explicitly given for each building element. Each construction method is linked to SE, so that a timed list of necessary equipment can be generated. Nevertheless, additional SE might be required and implicitly identified.

Dimensioning, the determination of necessary and economic dimensions according to the specific conditions and requirements of a construction project, is especially important for producing, transporting and storing facilities. Under-dimensioned elements can lead to a delay in construction progress (e.g. insufficient storage areas), or individual work steps could become impractical (for example if a tower crane's reach is too small). Over-dimensioned elements increase the costs (for example if the crane is higher than needed) and the travel times (if storage areas are too large and need to be crossed frequently).

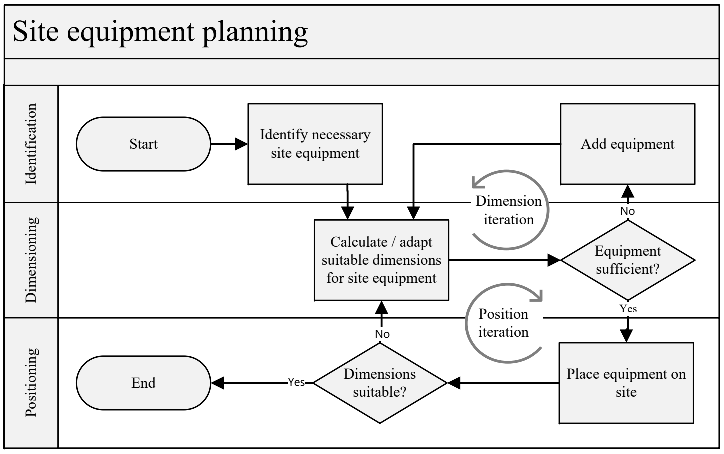


Figure 1: Site equipment planning and interdependencies of different planning stages

2.2. Knowledge-based systems

Knowledge-based systems are computer programs using methods from the field of artificial intelligence. They are used to assist humans in solving complex problems and tasks that are usually conducted by specialized decision makers. To that end, the algorithms mirror human thought processes and attempt to draw intelligent conclusions and action recommendations from given information [12].

2.2.1. Characteristics and architecture of knowledge-based systems

KBS are characterized by the strict separation of knowledge (stored in a knowledge base) and techniques to retrieve information from that knowledge (called inference engine). Further components are needed to fill the knowledge base (expert interface and knowledge acquisition component) as well as to retrieve solutions for a specific problem (user interface, working memory and explanation facility) [13]. The typical structure of a KBS is shown in Figure 2.

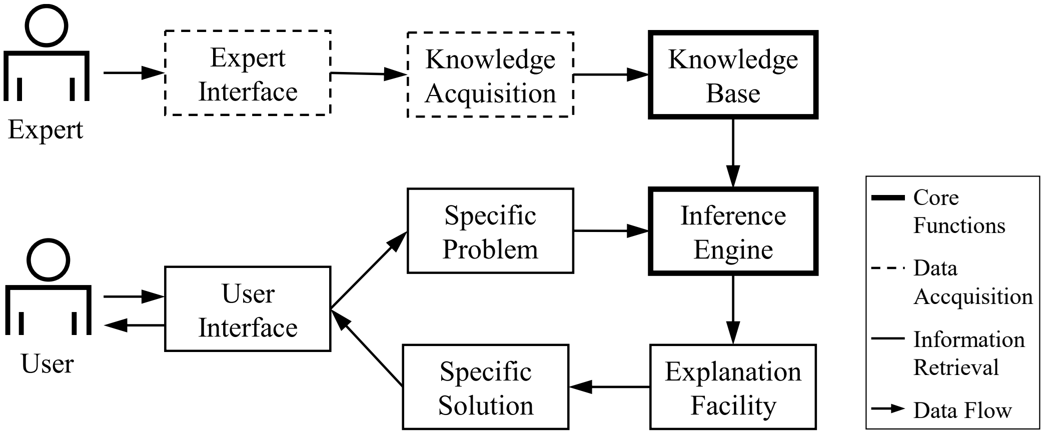


Figure 2: Components and data flow of a knowledge-based system

The core functionality of a KBS lies in the knowledge base and the inference engine. The *knowledge base* contains the permanent knowledge, which can be structured in rules and facts. Human knowledge comprises factual and heuristic knowledge. While factual knowledge can be directly represented by strict rules, heuristic knowledge is less rigorous and may lead to unexpected results, and is therefore rarely used in KBS [14]. The *inference engine* is the knowledge processing and reasoning component of the KBS. In analogy to the functionality of the human brain, it is able to generate answers, predictions or suggestions for a specific problem by the use of formal reasoning. Different types of KBS implement inference in different ways (see Section 2.2.2). The two fundamentally different types of inference that can be implemented in inference engines are forward chaining and backward chaining [12]. Forward chaining is the classical data-driven approach: the input data is known and a previously unknown solution is sought. Backward chaining is used, when the input data is not known, i.e. it generates possible input data to obtain a desired solution.

For the creation and expansion of the knowledge base with expert knowledge, a knowledge acquisition component and an expert interface are needed. The *expert interface* operates as input device for entering knowledge about the specific field of the KBS. The *knowledge acquisition component* inserts the data into the knowledge base. Knowledge can be entered and altered by human experts as well as by the KBS itself [15].

To generate and retrieve solutions for specific problems, a user interface, and an explanation facility are used. The *user interface* provides the communication between the user and the KBS. It may contain a graphical interface and different amenities to facilitate the interaction. The specific problems have to be converted to facts that can be processed by the inference engine. Temporary, case-specific data is stored in the working memory. This data includes both data inserted into the user interface as well as the determined solutions for this data. The *explanation facility* is used to control the generated solutions. An explanation of how the inference is drawn is critical to better understand how the system generates a certain solution, and to supervise the results in case of unexpected outcomes [13].

2.2.2. Rule-based knowledge inference systems

Regulations and instructions concerning SE are usually formulated in clear and precise rules that can be broken down to elementary entities. Usually, the correlations between requirements and solutions are concise and definite (e.g. the number of washing facilities per worker or minimal required crane capacities). Rule-based knowledge systems are well suited for problem domains that can be represented in modular rules. The human-readability and comprehensibility of the rules help to lower the acceptance threshold of engineers, and allow for easy rule definition and inspection. Rules are used to precisely describe elementary circumstances. They are typically in the general form of *WHEN* <situation or condition> *THEN* <action> [16], in contrast to the first-predicate logic of the aforementioned logic-based systems. More complex systems can be reduced to a set of elementary entities, with each entity being represented by one rule.

Rule engines are able to execute a set of rules intelligently by using algorithms such as the Rete algorithm [17]. They are able to support additional features, such as priorities, preconditions or mutual exclusion. Therefore, even complex cross-linked sets of rules can be evaluated efficiently.

While, indeed, the rule execution could be implemented using a procedural or object-oriented programming language, the use of a rule based system has decisive advantages. As the selection of construction equipment is highly interdependent, several iterations might be needed to create a suitable solution—when one element changes, other elements may have to be adapted. Several rules may refer to the same fact, which might lead to a loop—one rule changing the fact, and the other rule changing it back. Those conflicts may lead to an infinite loop of rule execution. Therefore, to process the set of rules through inference, it is insufficient to merely execute one rule after the other. There are different strategies to resolve these conflicts, e.g. the rule execution can be stopped after a certain number of loops (providing unpredictable results, and thus not recommended), the rules can be weighed by the user, or the inference engine can alert the user, who can solve the conflict by adapting the rules. Especially with knowledge databases growing over time, possible conflicts may be overlooked without conflict resolution strategy. The inference therefore provides support to establish a well-maintained, consistent rule base.

For management of the rules, it is advisable to use a business rule management system (BRMS). BRMSs include a repository to permanently store rules, an inference engine to manage the decision logic, and a runtime environment to connect both.

2.2.3. Advanced algorithms for rule processing

The Rete algorithm generates a discrimination network using all conditions given in the different rules. The network contains different types of nodes: root, object, 1-input, 2-input and terminal. All objects enter through the root node. Each condition is represented by a 1-input node. If a rule contains more than one condition, a 2-input node is used to combine each two conditions into one 1-input node. The output of the last input node is used as the input for a terminal node. The terminal node represents the action of a condition. During the first propagation of the fact, all conditions are checked and rules are fired where possible. The output of each node is stored. From the second propagation onward, the stored outputs are reused when the facts remain the same. Only conditions for altered facts must be checked, reducing the calculation effort significantly. However, as the interim results have to be stored, the memory usage can increase drastically (Forgy, 1982).

To better represent object-oriented data and to reduce the calculation effort further, the Rete algorithm was adapted. By adding further node types, the ReteOO (Rete-Object-Oriented) algorithm was developed [18]. The new node types are entry point nodes, object type nodes, alpha nodes, join nodes, and left input adapter nodes. Entry point nodes are located behind the root node. If several entry point nodes exist, the network can be split into several networks. For each object type used in the rules, an object type node is created. Object type nodes act as a barrier—they only propagate facts that apply to the following nodes. This way, facts are only checked against rules whose conditions demand the same object type. Alpha nodes expand the function of 1-input nodes to evaluate literal conditions. Left input adapter nodes are used to convert objects to tuples for following joins. Join nodes, or beta nodes, expand the function of 2-input nodes to find matches for rules with several conditions. Additionally, ReteOO adds enhancements such as node-sharing, where nodes can be shared when rules follow similar patterns.

After further development, the PHREAK algorithm was introduced [19]. PHREAK is characterized as lazy and goal-oriented, whereas Rete is characterized to be eager and data-oriented. Instead of instantly firing all rules, rules with all inputs satisfied are queued. Rules are then fired depending on their salience. According to JBoss Community [19], the PHREAK algorithm is additionally enhanced by adding three layers of contextual memory, stack based evaluations, isolated rule evaluation as well as rule, segment and node base linking.

3. Related work

Over the past few years, researchers have been proposing different approaches to automatic site layout generation. However, "there is no report that indicates the use of site layout models in the larger scope in the construction practice" [20], leading to the conclusion that convenient solutions have not been proposed yet. Intense investigation in the software market has revealed that especially the automatic selection and dimensioning of site facilities are widely neglected.

While various research groups have dealt with the optimization of construction site facility planning during the last decades, they generally use predefined SE and consider solely the positioning on site. Up until, there is no comprehensive implementation of the construction site setup problem, requiring extensive manual input for all approaches.

In the past, rule-based systems faced difficulties in user-friendliness and applicability. Limited resources in hard disk space and system memory restricted the scope and inference speed, impeding the broad implementation of rule based knowledge systems. With modern hardware and improved inference algorithms, new opportunities arise for user-friendly and comprehensive applications [21].

KBS have been used in different engineering disciplines, such as the automotive industry [22], aviation [23], or factory planning [24]. Likewise, digital assistance is widely available in several construction-related subjects. First approaches to using KBS for construction-related tasks have been published by Zozaya-Gorostiza et al. [25] and Moselhi and Nicholas [26]. Both groups are using expert systems to create working schedules. Hamiani [27] presented CONSITE, a knowledge-based expert system framework to solve the construction site layout problem. Tommelein et al. [28] used an expert system to designing construction site layout. In both approaches, construction site equipment objects are represented by rectangular surfaces and arranged on a 2D building site. Limits of the program lie in the need of laborious manual input, as well as the lack of transparency and the possibility to influence the generation.

Newer approaches use the advantages of BIM models as a rich information source, but again, are neglecting the automated selection of the SE. Researchers concentrate on heuristic optimization of the site layout. Huang and Wong [29] use a binary-mixed-integer-linear algorithm to optimize the site layout to achieve reduced travel times and set-up costs. Shawki et al. [30], Elgendi et al. [31], and Kumar and Cheng [7] propose the use of genetic algorithms to create construction site plans. The algorithms begin with random layouts, which are varied by crossing and mutation. The research also includes the use of meta-heuristic algorithms, such as swarm intelligence: Yahya and Saka [32] use an algorithm based on the behavior within a bee colony (artificial bee colony algorithm), Ning et al. [33] use an ant-algorithm (max-min ant system). Wang et al. [34] plan optimal crane positions on large-scale sites using the firearm algorithm. Schwabe et al. [35] use interactive rule checking to evaluate site layouts during the manual generation. Jin et al. [36] use a multi-attribute utility model for optimizing scaffolding placement and solving the productivity-tasks-scaffolding trade-off problem.

An extensive literature review on prior approaches to optimize site layouts is also provided by Huang and Wong [29]. Additional research has been conducted in the field of working areas. Akinci et al. [37] automatically generate project-specific work spaces from IFC models using a generic work space ontology. Guo [38] link an AutoCAD model with an Microsoft Project schedule to find and resolve possible work space conflicts.

In essence, it can be stated that while the construction site layout problem has been intensively investigated, the preliminary step of choosing and configuring SE and dimensioning site facilities has mostly been neglected so far. As however, SE plays a major role for the efficiency of the construction processes and is subject to numerous regulations, computational methods for supporting the process are strongly required.

4. Rules for Site Equipment Selection and Generation

To computationally process rules on how to select and dimension SE, they have to be formulated machine-readable. Business rule management systems usually follow the typical form of *WHEN*... *THEN*... and expect a particular data format. The specific problems have to be converted to facts that can be processed by the inference engine (knowledge acquisition, see Section 2.2).

For prototype implementation, we used the BRMS Drools, which provides a rule engine using the PHREAK algorithm. In Drools, rules are formulated using either the MVFLEX Expression Language, which allows simplified syntax, or in plain Java, when more complex functionalities are needed. We use the Java syntax. For better maintainability, an individual rule file has been created for each type of equipment.

Rules in Drools consists of the rule identifier, a left-hand side starting with the keyword *when*, and a right-hand side starting with the keyword *then* (Figure 3). The left hand side contains conditions for executing the rule. If the conditions are met, the commands on the right hand side are carried out. Values required on the right-hand side must be bound to a variable in the left hand side by using a colon.

Figure 3 shows show a rule for creating the needed size of a storage space. The left-hand side can be read as: “when material of type rebar is needed, and a storage space of type rebar is planned”, the right hand side means “calculate minimum side lengths and modify storage space accordingly”. The storage space of type rebar is bound to the variable $s (the use of the $-symbol is not mandatory, but encouraged for readability). For rebar, the minimum storage side length can be assumed as the length of the longest bar. The minimum side width can be depicted by the number of bundles, where a bundle is assumed to have the width of one meter. To get the required width in meters, the number of bars is divided by the number of bars per bundle. Information can be retrieved from the bound variables of the left hand site. With the keyword *modify*, the minimum side lengths are passed to the storage area utilizing the Java methods of the storage space.

```
rule "Storage size rebar"
    when
        $s : StorageSpace(type == "Rebar")
        $m : Material(type == $s.type)

    then
        double number = $m.getQuantity();
        double minWidth = number / (double)map.get("amountInBundle");
        double minLength = (double)$m.properties.get("Length");

        modify($s){setMinWidth(minWidth), setMinLength(minLength)}

    end
```

Figure 3: Rule for rebar storage size calculation

As addressed in Section 2.1, some site elements entail more degrees of freedom than others. In the following subsections, we present a proof of concept for rule-setting for five types of SE. The rules are arranged tabular, with the left side representing the when-statement, and the right side representing the then statement:

when	then

Out of the seven groups presented in Section 2.1, we chose tower cranes, concrete pumps, social and office facilities, storage areas, as well as traffic and transportation areas. These SE elements are highly versatile and strongly affect both the costs and the productivity of a construction site.

4.1. Storage areas

s1 calculate material consumption
Input: materials

material consumption is unknown	divide material needed by time needed for each job determine maximal consumption

s2 Propose optimal order quantity and maximal stock (economic order quantity) [39]
Input: material and order costs, safety time

maximal consumption is known	calculate maximal stock and order quantity determine maximal consumption

s3 Depending on the stored material, space requirements for storage vary. While rebars are usually stored in bundles side by side, smaller material is stacked and compactly packed. Items should not be stacked higher than 1.50 m to ensure good access. To prevent damage, some materials have maximum stack numbers.
Input: material stock, maximum stacking heights

material is rebar	calculate bundles from stock. storage length is rebar length, storage width is bundle width × bundles
material type is prefabricated or formwork or installation or bricks or bag or box	calculate maximal stack number, calculate stacks. Calculate minimum needed area.

s4 Interchangeable silos are used for storing bulk goods and fluids. There are several sizes available, however with standardized silos only the height changes with a consistent radius of 2.6 m. To change and use the silo, an adjoining shunting area is needed.
Input: number of silos

silos are needed	set silo radius 2.6 m set shunting area 8 m×10 m

s5 Operating materials are usually stored in small tool sheds.

sheds are needed	set shed footprint 3.00 m to 3.50 m

s6 Skips and waste containers are used to collect different kinds of waste on site. For each type of waste, a separate skip has to be provided to prevent from paying higher rates for mixed waste. Input: types of waste and volume between collections

waste volume is less than $5.50\,\mathrm{m}^3$	skip footprint is 3.20 m×1.80 m
waste volume is more than $5.50\,\mathrm{m}^3$	skip footprint is 3.60 m×1.80 m

4.2. Tower cranes

The selection of suitable tower cranes is subject to several interdependencies. If several tower cranes are needed, positions and dimensions of the tower cranes have to be planned thoroughly in order to avoid them obstructing each other. An initial tower crane setup can be created by the following rules, assuming that the primary crane will have each the highest capacity,the highest jib length as well as the highest hook height. For an economic layout, the dimensions of the tower cranes can be reduced later during selection of explicit crane types.

c1 Estimate necessary number of cranes by used construction methods. Several rules of thumb are available: estimation, how many workers one crane can serve; estimation over built volume; estimation over lifted weight [1, 40].

Input: construction methods, building volume, lifted weights

construction method is concrete pump	25 workers per tower crane
construction method is concrete bucket	15 workers per tower crane
construction method is mixed	10 workers per tower crane
construction method is prefabricated	3 workers per tower crane
volume is known	no. of cranes is built volume / (duration * 2000)
weight is known	no. of cranes is lifted weight * duration / 2000

c2 Propose minimum height of crane hooks, so that jibs don't interfere with each other and the environment [2].

Input: number of tower cranes, safety, obstacle, workspace and hanger height

first crane	minimal hook height = obstacle height + workspace height + safety distance + hanger
more than one crane	minimal hook height = height of highest crane + 10 m

c3 Propose minimum jib length if position of the crane is known, so that the entire construction can be spanned.

Input: construction coordinates, number of cranes, positions of cranes

first crane	minimal jib length is the longest distance from crane foot to vertex of construction
minimal jib length is higher than 75 m	return error: “Required jib length very high. Revise tower crane position!”

c4 Propose necessary crane capacity. Depending on the construction method, the highest loads vary. When performing bucket concreting, the concrete bucket is decisive, when using concrete pumps, the heaviest formwork element, and when deploying prefabricated elements, the heaviest element [40].
Input: construction methods

concrete bucket size not known	bucket size is user input or $1\,\mathrm{m}^3$
heaviest formwork not given in BIM model	heaviest formwork is user input
construction method is concrete bucket	minimal capacity is bucket size × $2.8\,\mathrm{kg\,m^{-3}}$
construction method is concrete pump	minimal capacity is heaviest formwork
construction method is prefabricated	minimal capacity is heaviest prefabricated element

c5 Different tower cranes have different footprint. The higher tower crane is, the more area is needed as footprint [2].
Input: tower crane heights

tower crane is lower than 70 m	minimal footprint is 4 m × 4 m
if tower crane is lower than 80 m	minimal footprint is 7.5 m × 7.5 m
if tower crane is higher than 80 m	minimal footprint is 10 m × 10 m

4.3. Concrete pumps

Concrete pumps are conditionally movable on site—during the course of construction, they frequently change their position on site. However, as opposed to freely movable equipment such as excavators, they have to be transferred to previously determined parking spaces due to their large footprints and the need to be accessible to cement trucks delivering fresh concrete.

p1 Calculate the minimal reach of concrete pump.
Input: construction method

construction method is concrete pump	minimal reach of concrete pump is maximal distance from building edge to construction element with construction method concrete pump

p2 Propose required capacity of concrete pump to comply with the working schedule .
Input: concrete volume, working schedule

construction method is concrete pump	minimal pump capacity is total volume divided by duration for each process step

p3 Concrete pumps are available in different sizes. Schach and Otto [2] divide them in 4 generalized groups depending on both the pump reach and the pump capacity.
Input: necessary pump capacity, necessary pump reach

capacity is lower than $150\,\mathrm{m}^3\,\mathrm{h}^{-1}$ and reach is lower than 27 m	small concrete pump is sufficient, maximal vehicle weight is 18 t
capacity is lower than $160\,\mathrm{m}^3\,\mathrm{h}^{-1}$ and reach is lower than 36 m	medium concrete pump is sufficient, maximal vehicle weight is 26 t
capacity is lower than $160\,\mathrm{m}^3\,\mathrm{h}^{-1}$ and reach is lower than 42 m	large concrete pump is sufficient, maximal vehicle weight is 32 t
capacity is lower than $200\,\mathrm{m}^3\,\mathrm{h}^{-1}$ and reach is lower than 63 m	large concrete pump is sufficient, maximal vehicle weight is 60 t
capacity is higher than $200\,\mathrm{m}^3\,\mathrm{h}^{-1}$	report error: “Task can’t be performed with one pump. Use several pumps to keep schedule.”
reach is higher than 63 m	report error: “Task can’t be performed with one pump. Use hose or piping system.”

p4 Depending on the size of the concrete pump, differently sized parking spaces are needed.
Input: size of concrete pump

small or medium pump	parking space should be 10 m × 7 m
large pump	parking space should be 13 m × 10 m
very large pump	parking space should be 18 m × 14 m

p5 To ensure full usage of pump capacity, parking spaces for two concrete mixers should be placed directly behind the concrete pump if possible. However, if not enough clear space is available, one parking space can be sufficient if shunting times are considered [1].
Input: number of parking spaces for cement trucks

number of parking spaces is 1	parking space should be 12 m × 3 m
number of parking spaces is 1	parking space should be 12 m × 6.5 m

4.4. Social and office facilities

The following rules cover the use of a 20 ft site container, which is mainly used in Germany. The outer dimensions of a 20 ft site container are $(l \times w \times h) = 6.06\,\mathrm{m} \times 2.44\,\mathrm{m} \times 2.59\,\mathrm{m}$, leading to a usable area of $13.88\,\mathrm{m}^2$ [10].

f1 Break and changing rooms need to be provided for the workers. Each break room should have at least $6\,\mathrm{m}^2$ footage and additionally $1\,\mathrm{m}^2$ per worker (ASR A4.2). One standard 20 ft container can hold 8 people [2].
Input: number of workers

no breakrooms available	plan one container for each 8 workers

f2 Sanitary facilities and toilets should be within 100 m reach of each worker (ASR A4.1). On smaller sites, usually portable toilet units are used, larger sites should provide sanitary containers with washing facilities. Sanitary facilities should be separated for men and women (in brackets). Other arrangements are possible.
Input: number of workers

less than 10 workers	1 (+1) portable toilet units
less than 25 workers	1 (+1) containers
less than 50 workers	2 containers
less than 75 workers	3 containers
...	...

f3 If more than 50 workers are occupied on site, a first aid room has to be provided (ASR A4.3).
Input: number of workers

more than 50 workers	add sanitary container

f4 On bigger constructions, offices need to be provided not only for the foreman, but for the site manager, specialist planners, contractor, etc. Schach and Otto [2] propose $8\,\mathrm{m}^2$ to $10\,\mathrm{m}^2$ per person.

Input: number of people needing office spaces

offices are needed	provide $8\,\mathrm{m}^2$, e.g. 1 container per 2 workers

f5 If the site is isolated and no hotels are booked for the workers, they need to be accommodated on site (ASR A4.4). One container can be used to accommodate 2 workers, however other setups are possible as well.

Input: accommodation on site, number of workers

accommodation is needed	provide one container for 2 workers

f6 Calculate the needed base area for all containers. If needed, maximal 3 containers can be stacked. Containers are usually placed long sides together.

Input: how many containers should be stacked?

containers are planned	total length is container length
no stacking	total width is number of containers × width of container
stack 2	total width is round up (number of containers / 3) × width of container
stack 3	total width is round up (number of containers / 2) × width of container lenth

t1 Decide, if construction road type is dead end or passage through site
Input: positions of site entry and exit

entry is also exit	construction road is dead end construction road is two way
entry is not exit	construction road is a passage construction road is one way

t2 Determine necessary construction road width and tractrices so that all vehicles can pass. Especially concrete pumps need higher passage widths. (see RAS-K-1 1988)
Input: road type, construction methods

construction road is one way	minimum curve radius is 10 m minimum road width is 3.5 m tractrix factor = 1
construction road is two way	then minimum curve radius is 10 m minimum road width is 6 m tractrix factor = 2
concrete pumps are used	minimum road width plus 0.5 m
construction road is curved	calculate tractrix expansion

t3 Determine necessary turning area for dead end roads.
Input: road type

construction road is dead end	require turning area

t4 Request user input for number of parking spaces and set dimensions (see MGarVO).
Input: number of parking spaces

number of parking spaces is bigger than 0	create n parking spaces with dimensions 5.00 m × 1.50 m

t5 Determine width of foot paths ([2])
Input: number of workers

less than 20 workers	minimum footpath width is 1.00 m
less than 100 workers	minimum footpath width is 1.25 m
less than 250 workers	minimum footpath width is 1.75 m
more than 250 workers	minimum footpath width is 2.00 m

Table 1: Information sources for executing rules on creating construction site equipment. ✓: information needed from this source; opt: information optional

Main group	Element	Rule	Input from			
			Preceding rule	User	BIM	Schedule
Storage areas	Storage areas	**s1**			✓	✓
		s2	**s1**	✓		
		s3	**s3**	opt		
	Silos	**s4**		opt		
	Sheds	**s5**		opt		
	Waste	**s6**		✓		
Construction machinery	Tower cranes	**c1**			✓	✓
		c2	**c1**		✓	
		c3	**c1**	✓	✓	
		c4	**c3**	opt	✓	✓
		c5	**c2**			
	Concrete pumps	**p1**			✓	✓
		p2			✓	✓
		p3	**p1**, **p2**			
		p4	**p3**			
		p5	**p3**	✓		
Social and office facilities	Breakrooms	**f1**				✓
	Sanitary	**f2**				✓
	First aid	**f3**				✓
	Offices	**f4**				✓
	Accomodation	**f5**		✓		✓
	All containers	**f6**	**f1**,**f2**,**f3**,**f4**,**f5**		opt	
Traffic areas and transport routes	Construction road	**t1**		✓		
		t2	**p3**			
		t3		opt		
	Parking spaces	**t4**		✓		
	Foot paths	**t5**				✓

5. Prototype Implementation

To demonstrate and test the proposed approach, a prototype has been implemented. The prototype provides different features to support engineers during the planning of the construction process: generation of work schedules, generation of site equipment and generation of site layout plans.

5.1. System design

The system we propose in this paper identifies the SE necessary to execute a construction over the different phases of the shell construction. In a preprocessing step, we generate a working schedule from a 3D BIM model using coarse discrete event simulation. Information about the construction project retrieved both from the BIM model and the working schedule is processed in a KBS. The KBS generates the required characteristics for specific SE and proposes appropriate positions on the site. The final construction site layout is determined by the engineer in charge.

For data exchange between the different system components, a database is used. As the construction elements are highly interdependent on each other as well as the working schedule, several iterations may be necessary until an adequate site layout is created. A process scheme for the proposed concept is depicted in Figure 4.

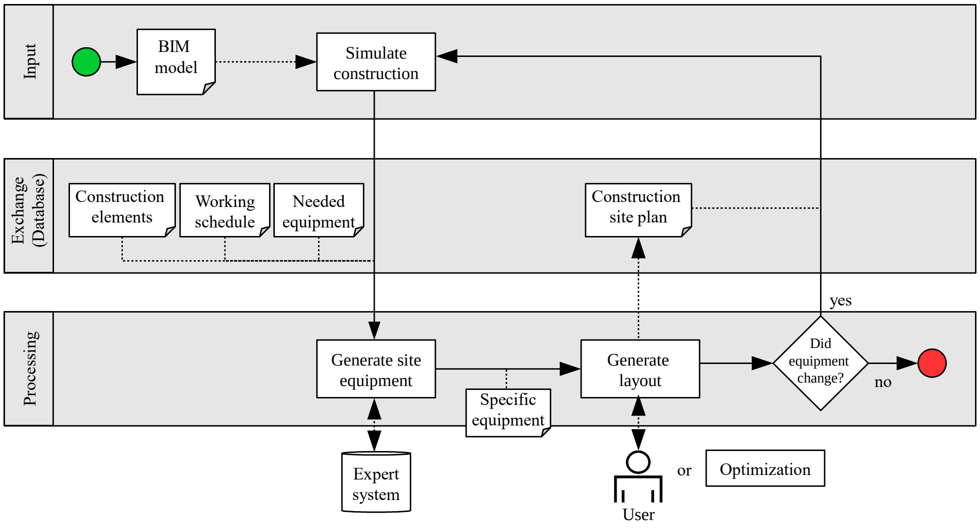


Figure 4: Process scheme for a semi-automated site equipment planning system

5.2. Preparation of the input data

For gathering information about the building to be constructed including materials, construction methods, dimensions as well as the constructions schedule the system makes use of a BIM model. The BIM model also provides information about the construction site, such as its boundaries and accesses. Additional information not provided by requested as user input.

As the system considers shell construction rather than the interior fittings, a BIM model with a low Level of Development (LOD 200—for definition of the LOD, see AIA [41]) is sufficient. This allows to plan the SE already in very early planning phases, preventing decisions for sub-optimal construction methods by considering the site layout and its constraints. We use BIM models in the vendor-neutral standardized format Industry Foundation Classes (IFC) Version 2x3. The BIM model can be created by means of any of the available BIM authoring applications capable of exporting IFC.

Using the BIM model, a working schedule is created in pre-processing. We propose using a discrete event simulation on coarse level of granularity (cf. [42, 43, 44]), however manually created working schedules can be used as well.

We prepare the input data using the software Ceapoint desite MD. By means of desite MD, the BIM model is semi-automatically linked to the working schedule. Each construction element is linked to a construction phase as well as the required construction processes—such as "strip formwork" or "install precast element." Each construction process is linked with the scheduled start and end times as well as the required resources—such as tower cranes, concrete pumps, or number of workers—to perform the process within the given time limit. Using a script in desite MD, additionally the following properties of all construction elements are retrieved from the BIM model: element ID, length, width, height, volume, formwork surface, estimated reinforcement, x- , y- and z-coordinates, and needed resources. For the data exchange, all information is inserted into an SQLite database.

5.3. Generation of site equipment

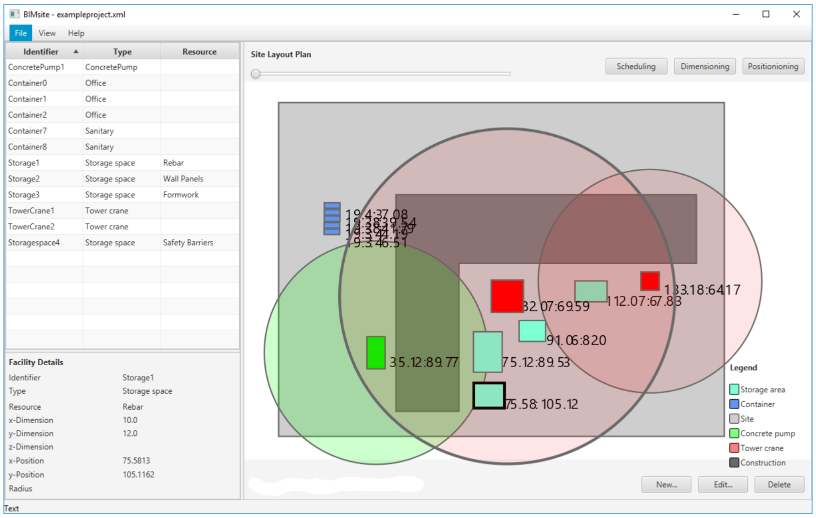
For generation of the SE, the rule based expert system presented in Section 4 is used.

5.4. Assisted generation of site layouts

For each equipment type, suitable placement areas are created and visualized in the user interface. The responsible engineer is subsequently placing the SE on the construction field in an interactive manner.

After finishing the site layout planning, the generated SE is stored in a database (type, characteristics and location of piece of each equipment) and used to reevaluate the working schedule considering the SE. For example, process times could speed up when two tower cranes are placed instead of one. If the working schedule has to be updated, the SE might change as well. If no changes are necessary, the process is terminated.

All SE elements can be modified for special user requirements by the user at all times, and additional SE can be generated by hand. A screenshot of the graphical user interface is shown in Figure 5. On the right-hand side, a 2D representation of the construction field is depicted. The SE is represented by their footprint and—for tower cranes and concrete pumps—their reach. On the left hand side, all generated site elements as well as details regarding selected elements are listed.



Identifier	Type	Resource
ConcretePump1	ConcretePump	
Container0	Office	
Container1	Office	
Container2	Office	
Container7	Sanitary	
Container8	Sanitary	
Storage1	Storage space	Rebar
Storage2	Storage space	Wall Panels
Storage3	Storage space	Formwork
TowerCrane1	Tower crane	
TowerCrane2	Tower crane	
Storagespace4	Storage space	Safety Barriers

Facility Details

Identifier	Storage1
Type	Storage space
Resource	Rebar
x-Dimension	10.0
y-Dimension	12.0
z-Dimension	
x-Position	75.5813
y-Position	105.1162
Radius	

Figure 5: Graphical user interface with 2D plan representation and interaction features

6. Case Study

To demonstrate and test the previously formulated rules, we use a pilot construction site made available for research by a construction company. In the following, we describe the construction project and how the rules have been used to propose different elements of SE.

6.1. Description of the construction project and available areas

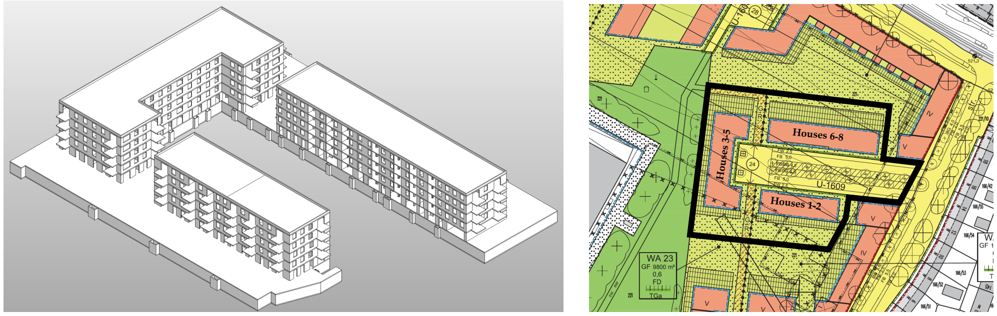
The pilot construction located in Munich, Germany, consists of a complex of eight 5-storey houses with a joint basement garage spanning the whole complex. The houses are arranged in U-shape, whereby the houses 1 and 2, houses 3 to 5 and houses 6 to 8 are connected to each other. Figure 6a shows the BIM model of the property. The total height from base to roof, gross floor areas and gross volume are depicted in Table 2.

Table 2: Heights, base areas of the standard floors, gross floor area and gross volume of the building complex.

Building	Height [m]	Base area [m^2]	Gross floor area [m^2]	Gross volume [m^3]
1-2	18	760	3800	13680
3-5	18	1080	5400	19440
6-8	18	960	4800	17280
Total	18	2800	14000	50400

The construction site is located within a larger densification area downtown (Figure 6b). Neighboring existing buildings and construction sites lead to restricted space on the construction field. To the north, northeast, south, and southeast, residential buildings are under construction. The area to the west is used for parking, and there is a residential road to the east, which functions as an access road to the construction site via a right turn.

The construction field has side lengths of approximately 100 m × 100 m, leading to a total area of approximately 10 000 m^2. No elements such as trees or existing buildings have to be preserved on the construction field. The excavation is sloped to the north, east and south. To the west, interpile sheeting is used to maintain the existing parking spaces. Areas usable for construction SE include a strip of about 7 m width between the excavation



(a) Building information model of the pilot construction in LoD 200.

(b) Development plan showing the new building complex as well as the neighboring properties. The construction border is marked in bold.

Figure 6: BIM model and development plan of the pilot construction site.

pit and the construction site border to the south, the open space of approximately 2600 m^2 in between the buildings (inner courtyard), which must also be used for the construction road as well as small openings of approximately 150 m^2 between houses 2 and 3 and houses 5 and 6, respectively. After completion of the respective ceilings, the floors of the buildings can be used for storage. In particular, the coverage of the parking garage increases the available storage space at ground level in the north and south by about 1000 m^2 each. Figure 8a depicts the areas usable for SE. The construction progresses counterclockwise, starting with house 8. All structural components are made from concrete cast in situ, using bucket conveyance for the walls and concrete pumps for the ceilings. Figure 7 shows a stitch created from aerial photography of the pilot construction site.

6.2. Application of the rules

6.2.1. Construction road

As the first step of the SE planning, the route of the construction road is planned. Using the rules defined in Section 4.5, minimum areas are determined for the necessary traffic areas. Input from BIM model and working schedule: floor plan of the construction site with entrance, number of workers. User input: number of parking spaces.

t1: Entrance = exit ⇒ dead end

t2: Two-way street ⇒ minimal width = 6 m, width at tractrices = 14 m

Figure 7: Top view of the construction site

t3: Dead end ⇒ minimal turning point area = rectangle with side lengths 18 m × 10 m

t4: User input: “3 parking spaces” ⇒ area for parking spaces = 5 m × 4.5 m

t5: Number of users in working schedule = 30 ⇒ width for footpaths = 1 m

Manual positioning: The construction road is placed in the center of the inner courtyard. Footpaths are distributed over the construction site to allow safe passage to all areas (Figure 8b).

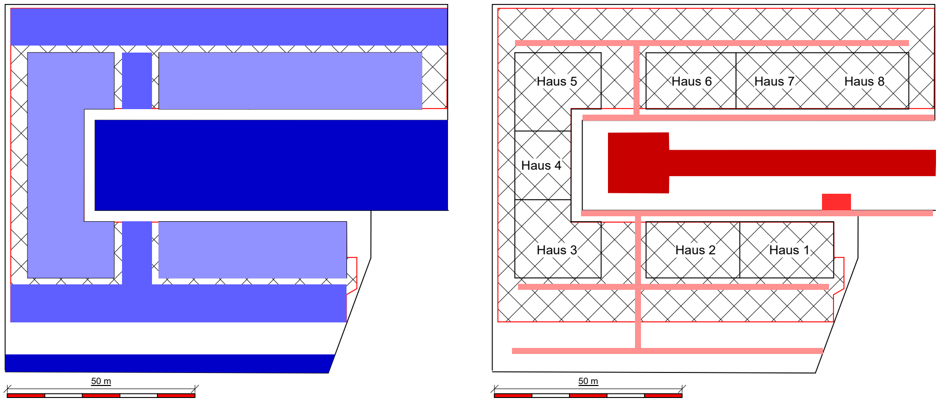
6.2.2. Tower cranes

Due to the dimensions of the building complex (maximum extension in the diagonal SI 120 m) and the traffic through concreting, three cranes must be provided to fulfill the construction schedule. Input from BIM model and working schedule: scheduled building elements, number of workers. User input: positions of pre-dimensioned cranes.

c1: Number: 30 workers, mixed construction methods ⇒ 3 tower cranes
$50\,400\,\mathrm{m}^3$ ⇒ 3 tower cranes

c2: Hook height: crane 1 ⇒ 25 m; crane 2 ⇒ 35 m; crane 3 ⇒ 45 m

Manual positioning: There are several possibilities to place the tower cranes on site Figure 9b. After the positions have been chosen by the planner, the necessary jib lengths can be calculated.



(a) Available areas on site. Dark blue: usable during whole construction. Medium blue: usable after completion of basement ceilings. Light blue: usable after completion of respective floors. Not marked: safety area and slope.

(b) As planned traffic areas on site. Dark red: construction road and turning plate. Medium red: parking spaces: Light red: foot paths.

Figure 8: Available areas on site and traffic areas.

c3: Jib length: crane 1 ⇒ 40 m; crane 2 ⇒ 45 m; crane 3 ⇒ 55 m

c4: Max load ⇒ concrete bucket: crane 1 ⇒ 2800 kg at 40 m; crane 2 ⇒ 2800 kg at 45 m; crane 3 ⇒ 2800 kg at 55 m;

c5: Footprints: crane 1 ⇒ rectangle with side lengths 4 m × 4 m;
crane 2 ⇒ rectangle with side lengths 4 m × 4 m;
crane 3 ⇒ rectangle with side lengths 4 m × 4 m.
Check, if tower crane footprints fit on proposed locations.

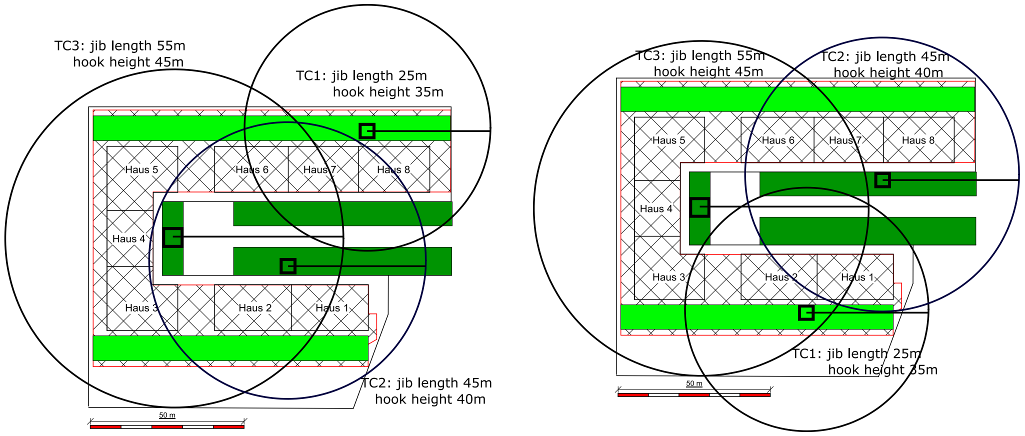
6.2.3. Concrete pumps

Input from BIM model and working schedule: scheduled building elements. User input: number of cement trucks.

p1: Reach: houses 1 and 2 ⇒ 30 m; houses 3 to 5 ⇒ 40 m; houses 6 to 8 ⇒ 40 m

p2: Capacity: houses 1 and 2 ⇒ $90\,\mathrm{m}^3\,\mathrm{h}^{-1}$; houses 3 to 5 ⇒ $140\,\mathrm{m}^3\,\mathrm{h}^{-1}$; houses 6 to 8 ⇒ $140\,\mathrm{m}^3\,\mathrm{h}^{-1}$

p3: Size: houses 1 and 2 ⇒ medium; houses 3 to 5 ⇒ large; houses 6 to 8 ⇒ large



(a) (b)

Figure 9: Two possible examples for tower crane setup. Dark green: Usable during the whole construction. Light green: Feasible with opening or sufficient load capacity in basement ceiling.

p4: Parking spaces: houses 1 and 2 ⇒ rectangle with side lengths $10\,\mathrm{m}\times 7\,\mathrm{m}$;
houses 3 to 5 ⇒ rectangle with side lengths $13\,\mathrm{m} \times 10\,\mathrm{m}$;
houses 6 to 8 ⇒ rectangle with side lengths $13\,\mathrm{m} \times 10\,\mathrm{m}$

p5: cement trucks: user input “two cement trucks” ⇒ rectangle with side lengths $12\,\mathrm{m}\times 6.5\,\mathrm{m}$

Manual positioning: Concrete pumps need rather large parking spaces, especially when they are fed by two cement trucks. To reduce the necessary reach and thereby the operating costs, the concrete pump may be moved to a different parking space. Possible parking spaces for the concrete pumps are depicted in Figure 10a. Check, if pump reach is sufficient from appointed parking space.

6.2.4. Social and office facilities

Input from BIM model and working schedule: number of workers. User input: site accomodation, stacking of containers.

f1: 30 workers without office ⇒ 4 break and changing containers needed

f2: 35 workers in total ⇒ 1 sanitary container needed

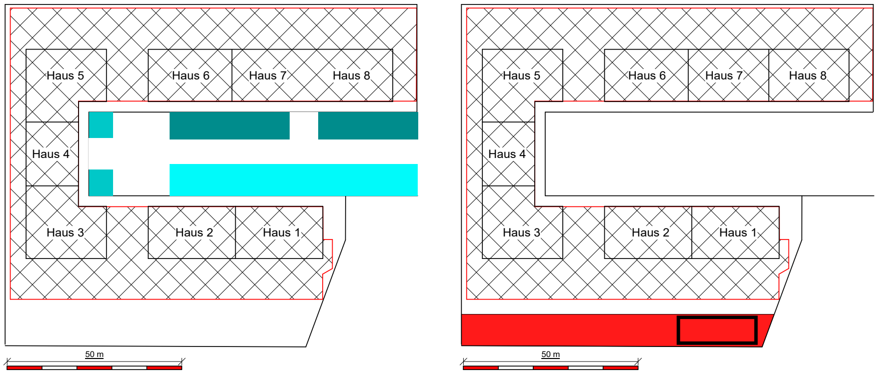
f3: 35 workers in total ⇒ no particular first aid container needed

f4: 6 workers with office ⇒ 6 office containers needed

f5: user input: “no on site accommodation” ⇒ no accommodation needed

f6: 11 rooms + 3 sheds = ⇒ 14 containers. User input: “stack two containers” ⇒ rectangle with side lengths 17.5 m × 6 m

Manual positioning: Closed rooms should not be placed within the working area of the tower crane. To prevent obstructions in the construction progress, social and office facilities should be placed on the sidelines of the construction site. The most convenient position for the containers outside the main focus of the construction work is on the south boarder of the construction field. By placing the containers in the south east corner, both the driveway and the construction site are overseen from the offices.



(a) Feasible positions for concrete pumps and cement trucks in different construction phases. Dark cyan: Phase one. Medium cyan: Phase 2. Light cyan: Phase 3. Black: Final positions.

(b) Feasible (red) and best (black) positions for containers.

Figure 10: Feasible and final positions for concrete pumps and social facilities.

6.3. Evaluation of the proposed system

The results show that the proposed semi-automated procedure for construction equipment selection and generation renders reasonable configurations.

6.3.1. Comparison to manual layout planning

Fairly similar results appear when comparing the semi-automated process to the manual SE selection and generation that has been performed on site. The SE at the pilot construction site was not planned thoroughly beforehand, solely focusing on the tower cranes and the container village. It is striking that the construction road and storage areas are merging, leading to an unclear traffic solution with insufficient horizontal clearance. A preliminary preparation of the construction road may have lead to a more concise layout. The setup of tower cranes generated by the knowledge based system is very similar to the setup planned by hand. The resemblance is due to the strict schedule demanding 3 tower cranes. Table 3 lists results for both methods.

Table 3: Comparison of results contained from knowledge based system and as-built construction site

Elements	Knowledge based system	Pilot construction site
Tower cranes	1: height 25 m, length 40 m 1: capacity 2800 kg 2: height 35 m, length 45 m 2: capacity 2800 kg 3: height 45 m, length 55 m 3: capacity 2800 kg	1: height 25 m, length 45 m 1: capacity 2300 kg 2: height 35 m, length 40 m 2: capacity 2800 kg 3: height 45 m, length 55 m 3: capacity 3100 kg
Construction road	leads to tower crane 3 explicit turning area	leads to middle of court yard turning area vague
Container	number of containers: 14 south east corner	number of containers: 20 south east corner
Concrete pump	1: reach 30 m 1: capacity $60\,\mathrm{m}^3\,\mathrm{h}^{-1}$ 2: reach 40 m 2: capacity $140\,\mathrm{m}^3\,\mathrm{h}^{-1}$	no detailed information, however varying concrete pumps were ordered for different construction phases

6.3.2. Practitioneer's feedback

The analogies between manual and semi-automatic SE generation illustrate that the proposed system is able to generate realistic results based on the rules encoded. While exhaustive quantitative testing of the proposed approach is yet to be done, we spoke to several field experts to get qualitative feedback. Due to the uniqueness of construction sites regarding the construction project, the undertakings concerned as well as the conditions during planning and construction, it is difficult to make absolute statements regarding planning quality. There is no "most accurate" solution, which can be used to measure performance. However, in interviews with practitioners, we have received confirmation that support in evaluating real world conditions is highly welcome. It can be challenging to keep the overview during balancing extensive rules. Especially when estimating and re-evaluating various alternative construction options, a semi-automated approach to SE-planning reduces the workload.

7. Conclusions

Site equipment planning is a complex task for which a multitude of boundary conditions, rules and considerations have to be taken into account. Today this task is accomplished mostly manually, as only little computational support is available. This results in a laborious and error-prone process. To better support site planners, a knowledge-based system for SE selection and generation has been presented in this paper.

The system is based on a comprehensive knowledge base compiling SE rules from different sources, including regulations, handbooks and best practices. A number of exemplary rules were presented in the paper and details of the system implementation were discussed. The developed system design makes use of a BIM model providing a rich information source regarding material and construction processes. As a result, the system creates the required construction equipment including its parameters and taking all dependencies into account. In addition, it creates possible placement areas on the site layout. The developed prototype and the presented case study provide a proof of concept.

In interviews with field practitioners, we gained the following feedback: Under real world conditions, finding optimal parameters for SE problems is always challenging. It is difficult to find appropriate solutions taking into account a wide range of different requirements that have to be fulfilled simultaneously. Digital assistance is, according to the interviewed experts, a highly promising approach to enhance the planning process. Beginning with the facilitation of SE selection opens further possibilities.

A major limitation of the proposed approach is that the selection and dimensioning rules must be first acquired and formalized. This is particularly challenging for tacit and experience knowledge, which however, forms a very important part of construction management. For this reason, the possibility of manual intervention by the user plays an important role in the presented concept. This also applies to the placement of the individual facilities, which is also performed manually. In essence, a fully automated process is neither possible nor intended in the moment as many decisions regarding SE and site layout require comprehensive contextual knowledge relying on human experience that cannot be completely formalized.

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