Rule-Based Generation of Assembly Sequences for Simulation in Large-Scale Plant Construction

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Abstract –
The efficient construction of large industrial plants (e.g. concrete plants, chemical plants) in high quality requires precise planning and execution of the individual logistics and assembly steps. For this purpose, detailed step-by-step instructions should be prepared that can be clearly interpreted and thus implemented by the staff on site carrying out the work. Especially meaningful and project-specific assembly instructions are very important. In some cases, digital plant models are already being used to visualize the assembly sequences. The individual steps of assembly are animated together with the associated plant elements, staff and other resources. However, the exact assembly sequence has to be specified by a production engineer. This paper presents an approach for semi-automatic generation of step-by-step instructions for assembly in large-scale plant construction. Basic information for the assembly of a plant can already be taken from digital (BIM) models (BIM: Building Information Modeling). They include, e.g., information on components, construction details and connections. Based on this information, specific assembly sequences can be defined as rules for various plant groups. These rules are collected in a central database and provided for further use. An example shows how individual assembly sequences can be generated based on a digital plant model using the rule set. The results can be made available as 4D animations to the involved employees on the construction site. The assembly sequences defined for a project can provide useful support for planning the processes on the construction site (assembly, transport and storage of building elements). A simulation provides the validation of the planning created for this project and therefore also the validation of the defined assembly processes.

Keywords –
Logistics Scheduling; 4D BIM; Plant Construction; Assembly Sequencing; Simulation

1 Introduction

Precisely coordinated individual construction site logistics are of great importance for the efficient and cost-effective handling of large-scale plant construction projects, especially when the transport and storage of very sensitive and large components are involved. Planning includes the selection, design, dimensioning and optimization of processes, material flows and resources. Depending on the complexity of the large plant, many different boundary conditions must be considered in the project-specific planning of site logistics. Therefore, planning is a very error prone and time-consuming process, exacerbated by the fact that it is usually performed manually. Even for the most motivated companies, the effort required for the first draft of a schedule can be so taxing that resources for an improved schedule are not available [1]. The automated planning and control of construction site logistics for such large-scale projects have not been sufficiently supported by digital planning tools so far. Today, planning and control of construction site logistics require extensive project experience. If transport and storage conditions are not properly analyzed and adhered to, not only can installation delays occur, but also damage to sensitive system components. In the worst case, reworking or complete disassembly may be necessary. In order to ensure that components are only delivered when they can be stored as required or directly installed, it is necessary to know the exact sequence of construction in advance.

Digital models have also been used for several years in large-scale plant construction for the planning and prefabrication of plant components. However, the digital models are hardly used on site, e.g. for controlling processes on the construction site. Even though digital building models do exist, only low-detailed assembly sequences, if any, are currently created by hand and given to the workers carrying out the work in the form of a manual, but the sequences are usually only determined on site. Even if plant components can be visualized on the construction site with the aid of mobile devices, there is currently no IT-supported assistance for compliance with a previously created assembly sequence. Certain information for the exact planning of the construction sequence is already available on the basis of the digital model or can be supplemented by categorizations based on our previous work [2]. However, the existing information is not sufficient for an assembly sequence and has to be systematically supplemented and properly linked.

In our approach, we use geometric attributes and other IFC (Industry Foundation Class) model information in conjunction with a model-specific set of rules to create an assembly sequence that can be transferred into a 4D model by adding the respective performance factor. On this basis, the warehouse logistics, means of transport and shift schedules of the construction workers required for the respective component and assembly tasks can be planned.

2 Related Work

In contrast to industrial production, there are significantly more uncertain factors in construction projects that need to be taken into account during the planning stage and to which a quick and efficient response is required. The basis for the execution of a construction project is the schedule, which is nowadays manually defined by project managers based on their experience and linked to the construction elements. Even the linking of costs and schedules is still done manually today [3]. This is a time-consuming planning process. The project plan is only adjusted in case of interruptions due to due to material shortages caused by delivery delays, lack of storage space or weather conditions [4]. In a global view of construction projects, little attention is given to the logistics on the construction site. Thus, unforeseen events cause delays to the entire project schedule. These delays could be minimized by an iterative re-planning of the project plan based on the current construction status.

In the construction industry, the transition to digital construction planning is mainly taking place with the help of BIM. The BIM methodology allows a seamless transfer of construction project information throughout the entire product life cycle. This is achieved by linking geometry information with other relevant information. With the right BIM management software, this linked data can be used for visualization, checking for compliance with rules, collision detection, assignment of schedules to components (4D), cost estimation (5D) and the generation of construction plans.

As part of our research, we have already developed an approach for linking BIM with logistics information, especially for large-scale plant construction. We created the method of classifying required logistics information for each element and storing it in form of an OWL-formatted ontology (OWL: Web Ontology Language) [2]. A created ontology represents a knowledge model with information for planning and controlling logistical processes on the construction site. The information in this ontology forms the foundation for the generation of assembly sequences in a construction project as used in the methodology presented in this paper. With the help of BIM management software and the extension developed, it is possible to assign any elements to these categories, thus enabling identification for our methodology presented in this work.

In contrast to the collision database shown in this paper, Borrmann and Schraufstetter implemented in their research metric operators of an SQL (Spatial Query Language) with octree and B-Rep approaches to reflect distance relationships between spatial objects [5]. Daum and Borrmann extended this SQL-based approach by a method for its topological and directional predicates which operates directly on the boundary representation [6]. Liu, Lei et al. developed an automatic scheduling approach exclusively for panelized construction in residential buildings [7].

3 Methodology

We developed an approach consisting of two steps to determine an automatic assembly sequence. In a first step, a sequencing of element by element according to the ascending Z-axis is generated. Basically, this procedure is logical for most elements, as the lower edge of an element usually rests on the upper edge of the element below. However, when generating assembly sequences based exclusively on the Z-coordinate of elements, it becomes apparent that logical errors can occur, for example when elements are levitating without being connected to a support structure.

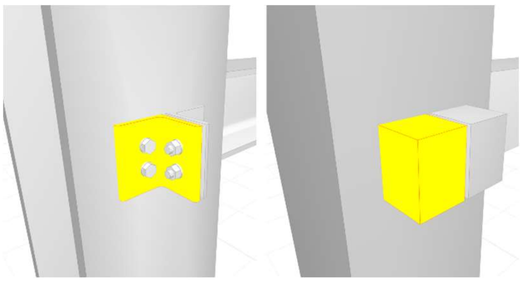

Figure 1. Model elements and corresponding bounding boxes

Therefore, in a second step it is necessary to determine whether all elements located under or next to an element and touching the element in question have already been built. Although there is the possibility to link elements in construction software, these links are not necessarily created for each element. Thus, we determine such links for any IFC model ourselves. To determine these links between elements, we use the bounding boxes of the elements and define an offset within other elements as shown in Figure 1. We then compare the bounding boxes of each element with those of all other elements and check for overlaps. In the example above (Figure 1), a collision is found between the angle cleats and the column, due to a defined offset which slightly enlarges the bounding boxes, but not between both angle cleats. Using these overlaps, a collision database is created in which all collisions per building element are recorded. This procedure offers a great performance advantage for the actual creation of the construction manual, as the database only needs to be created once for each model and thus in the following steps different rule sets can be applied and tested with little time expenditure. As soon as the rule sets have been defined correctly, i.e. completely, the construction sequence for each element can be determined. In doing so, each foundation is considered separately so that processes can easily be parallelized if necessary.

To be able to assign the construction rules to the individual building elements, these building elements must first be assigned to the ontology categories. We have provided two different methods for this: On the one hand, an automatic assignment can be carried out using regular expressions. These regular expressions must either be stored in the ontology for each category or can be defined in a *JSON* (JavaScript Object Notation) database. This is to achieve that in the best case all elements can be automatically assigned to a category with the help of regular expressions. Once this step is completed, the user can display all elements that could not be automatically assigned and thus the user can assign them manually to the categories of ontology. If desired, the manual assignment can be performed globally for the entire model, if elements with similar names are present. The available categories are taken from a direct connection to an *Apache Jena FUSEKI* ontology server, where a created ontology is uploaded (see Figure 2). If a required category is not available in the ontology, it can be created directly via the software extension developed by us and transferred to the ontology. After all elements have been assigned to a category, an assembly sequence can be defined using the rule database and collision database. The creation of the rule database and the creation of the assembly sequence is explained in the next chapter. The assembly sequence as well as the logistics information per element can be provided at the output. With the help of a provided effort value database it is also possible to create a schedule for the construction process from the assembly sequence and to validate it together with the geometric information from the 3D model in a simulation study, see chapter 5.

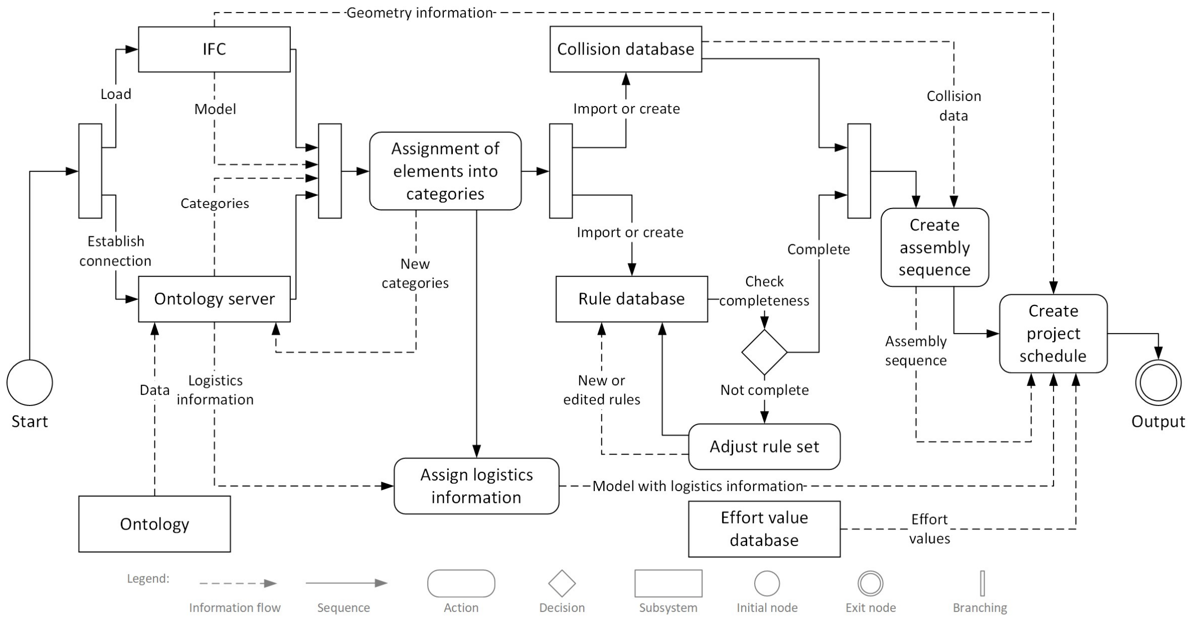

Figure 2. General methodology

4 Automatically Generated Assembly Sequencing

To specify a construction sequence, a rule database is required in addition to a collision database and components classified in categories of the created

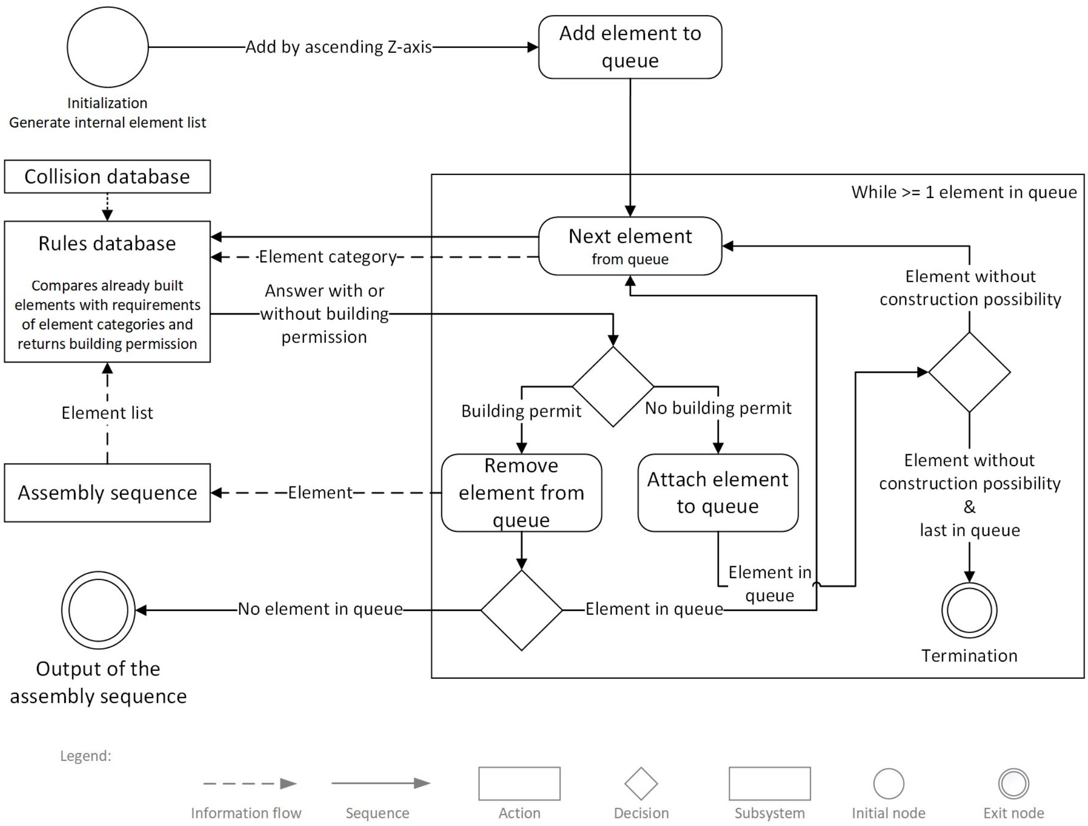

Figure 3. Rule-based assembly sequencing methodology flowchart

ontology. The rule database contains rules for assigning certain numbers of components to other components with AND connections. For each component, different rules can be linked together in the form of OR links. Since this is not a physics simulation, any torques occurring on components are not tolerable and must therefore be prevented by the rule set.

As an example, the rule set for the construction of a beam disregarding joining elements is shown below. The following rules apply to the construction of a beam:

Column(2)
∨
Column(1) ∧ Beam(1)
∨
Beam(2)

Figure 4. Example rules

The beam can therefore be attached either to two columns, one column and one beam, or to two beams as shown in Figure 4. This ensures that there are always two supports for the beam, so that no moments can occur at the supporting structure or the beams themselves and allowable moments in beams [8] and other parts can be neglected. When the rule set is defined, the construction manual can be generated. As shown in Figure 3, we start our rule-based assembly sequencing with the generation of an internal object list. This list contains all building elements which are then added to a queue by their ascending Z-axis. This ensures that the order of the objects is as close as possible to the actual order because we focus on buildings that are generally built from the bottom to the top. For a bridge construction, for example, two-way sorting would be necessary. Now the next element is taken from the queue in a loop and its category is passed to the rule database. The rules database compares already built elements with the requirements of the category of this element and returns a building permission or not. If the element receives a building permission, it will be appended to the building order. In the next step (not shown in the figure), the system always checks directly, independently of the queue, whether neighboring fastening elements (bolts, angle cleats and welds) can be built according to the rule set. If so, all required fastening elements will be immediately attached to the element to be fastened in the construction sequence, followed by the element to be attached. If the element has not received a building permission, it will be reattached to the queue. If there are no further building permissions and it is the last element in the queue, the rule set used will not be sufficient and the generation of the assembly sequence will be aborted. Otherwise, the element is reattached to the queue so that it can be built later. If the element has received the building permission, it will be added to the building order. The construction sequence also serves the rule database as a basis for the decision. If there are no more objects in the queue, the assembly sequence can be output.

4.1 Case Study 1 – Simple Steel Construction Model

For the validation of our methodology, a simple steel construction model containing 78 elements is used as shown in Figure 5. Despite its low complexity, the design features correspond to an actual steel construction model. The model has two storage areas and simple steel structure on top of a concrete foundation. The steel construction consists of four columns and five beams with two concrete slabs on top, 60 bolt connections (in 30 groups), 16 angle cleats, 16 anchor rods and six steel plates (two of which are already welded to a beam before installation (pre-assembled)).

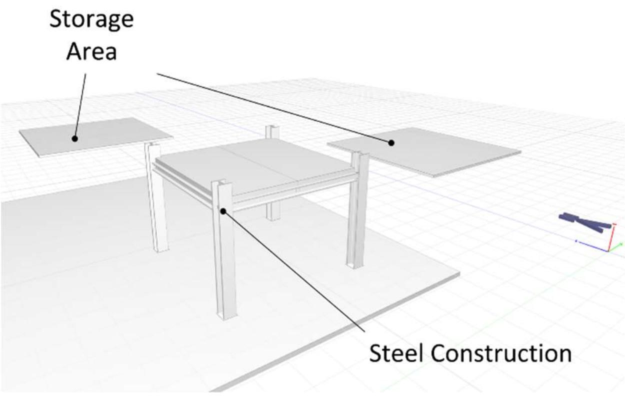

Figure 5. Overview of the simple model

After completion, this model is exported in IFC format and finally imported into *DESITE MD*. Using the software we developed, the elements of the model are then divided into categories of the ontology according to the methodology [2]. This is achieved using the implemented procedure, which matches elements by their names using regular expressions and automatically categorizes them. The collision database is created with an offset between elements of −0.02 m for the bolts and 0.03 m for all other elements. The collision database is checked against the model to ensure that all elements have collisions and that all elements of the model are considered in the later generated assembly sequence. Afterwards the rules for the assembly manual are defined. These can be quickly and easily adapted by using our rule editor. Once the rule set is defined, it is tested by creating an assembly based on it. To check the correctness of the rules, it has to be possible to create an assembly instruction in the first instance without causing any errors.

In the second step, the correctness of the building sequence is checked by an expert. Special attention is paid to whether the sequence is logical and consistent, for example, that no elements are built until elements that were not previously required have been built and thus no elements are levitating. If problems are found during the check, the rule set will be adjusted and then re-tested. Here, both the linking rules and the prioritization can be modified. To clarify the dependencies between the elements and to identify possible sources of error, the construction plan can be visualized as a Work Breakdown Structure (WBS). Figure 6 shows an example of the construction plan for a beam:

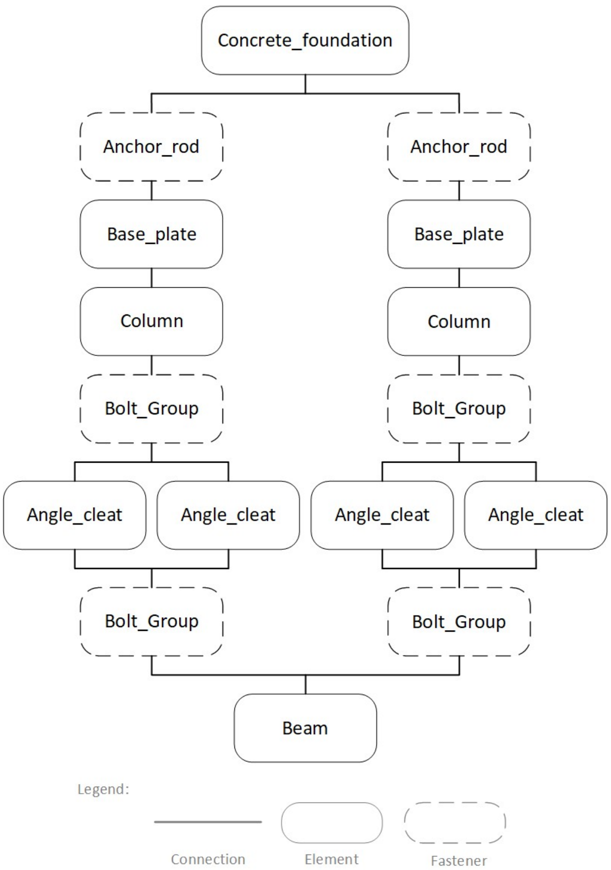

Figure 6. WBS graph of a beam

To build the beam, 15 additional elements are required, with the dashed elements representing connecting elements. Thus, the WBS shows the connection concept and not the construction sequence, since, for example, the final beam is first inserted and then directly bolted to the bolts. The advantage of the WBS illustration is that parallel processes can be identified. In addition, it offers the possibility to develop strategies to compensate for bottlenecks in a WBS branch by first building other branches for which all materials are available.

4.2 Case Study 2 – Complex Model

Once the assembly schedule for *Case Study 1* has been successfully created, we test the developed rule set on a more complex real model. The complex model is a section of a plant construction project of *thyssenkrupp Industrial Solutions* and contains 780 elements. To ensure general compatibility, the model is reduced to a steel construction tower as shown in Figure 7. The model consists of 16 concrete elements, 16 anchor rods, 4 base plates, 4 columns, 8 beams, 14 vertical bracings, 114 plates and 221 miscellaneous elements, connected with 94 bolt assemblies and 216 weld connections. Since the model was engineered in *Trimble Tekla Structures*, it has a completely different terminology. Therefore, the first step is to adjust the regular expressions to assign the categories of the created ontology. The first attempt to create an assembly sequence shows that the previously developed set of rules is not sufficient. A closer examination of the issue reveals that the existing categories of the ontology are also not sufficient.

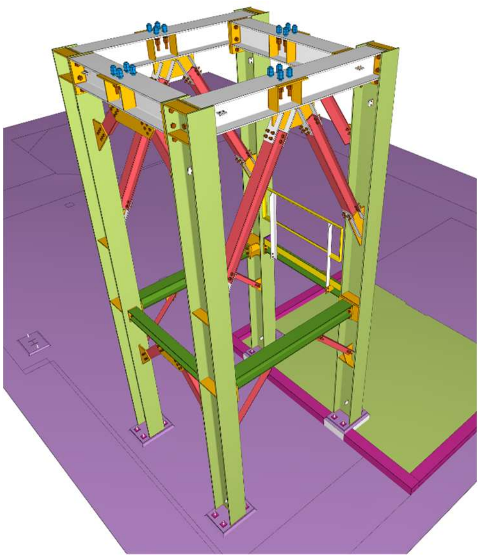

Figure 7. thyssenkrupp steel construction tower

Therefore, different categories are created via the communication link to the ontology server (as shown in Figure 2), especially for the fasteners that were previously assigned to only one category.

Based on this, the rule set is extended and tested using the collision database. After a few iterations the assembly sequence can be correctly created. This comprises 713 individual steps. However, a detailed step-by-step analysis shows that the assembly sequence for the diagonal beams is not logical, because one end of each beam has no direct connection. This problem is solved by recreating the collision database with a lower offset of 0.015 m to prevent the detection of a false number of required building elements in the surrounds.

5 Detailed Validation using Simulation

The detailed validation of the method for creating the assembly sequence is carried out with the help of discrete event simulation. For this purpose, the processes on the construction site are first planned. The generated assembly sequence is an essential prerequisite for a detailed analysis of the construction site assembly and the logistics processes. Using a generated assembly sequence (e.g. the simple model of Case Study 1 with 78 elements), a detailed BIM-based model and related information from the developed ontology, planning of processes on the construction site is carried out. For this purpose, different planning scenarios are defined for the processes on the construction site. In the planning scenarios the construction and logistics activities as well as the planning-relevant properties of the construction elements and materials of the building project are considered. For the creation of the scenarios, the assembly sequences specified by the construction plan and the dates of delivery of building materials are considered in detail. For the representation of scenarios, *Gantt* charts are used in planning. In the *Gantt* diagram, the individual deadlines of the planned processes on the construction site (such as transport, storage, and assembly) and the delivery schedules are coordinated. In addition, information from the ontology (e.g. requirements of building materials for storage and transport on the construction site) and formal descriptions of the processes are used to design the processes.

To enable simulation to validate the automatically generated assembly sequences, the defined processes on the construction site (such as the sequence of assembly, transport and storage) as well as the use of available resources (such as storage areas or transport equipment) need to be modeled. The planned processes, restrictions and resources can then be validated by simulation. For this purpose, material flow simulation models are built in *AnyLogic* based on the supplemented BIM model. Validation scenarios are experimentally examined using the simulation model. The simulation model provides valuable performance data in advance of construction activities and checks the planned equipment of the construction site (material flow and storage technology) and the planned deadlines.

In the following, this simulation-supported procedure is discussed for Case Study 1 – Simple Steel Construction Model (see Figure 8). For the execution of the simulation-supported validation of the construction manual, in addition to the data from the BIM model, the layout and the prepared construction plan (see section 4.1), assumptions are made regarding the dates of delivery of the components, personnel deployment and resources on the construction site. When designing the planning scenarios, it is necessary to know the exact construction sequence and deliveries in advance, because they are coordinated with each other and thus transports and storage on the construction site need to be planned.

Information on material and resource requirements for each process (e.g. storage conditions for steel beams) from the ontology (see [2]) is used to design transport and storage.

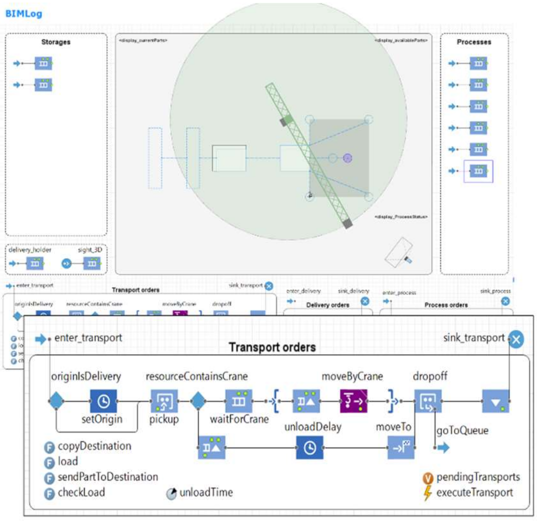

Figure 8. Example simulation model for Case Study 1 – Simple Steel Construction Model

In the simulation model (Figure 8) the layout, the positions of the six assembly locations of the elements, and the project-relevant processes (such as the assembly queues in the *Processes* area and the storages in the *Storages* area) are formalized. The processes sequences (transport by crane, deliveries to the construction site, as well as assembly and pre-assembly) are built in the simulation model (see Figure 8). The modeled processes conform to the generally valid process description at the construction site. They can therefore be extended, adapted and reused for new construction projects or planning scenarios. The relevant process sequences are used in the simulation according to the planning scenario.

The resources planned for the project are one crane, one crane operator, and one worker. The planning data from a defined scenario is implemented in the simulation model as tables, e.g. bill of materials for each construction process, scheduled deliveries to the construction site, scheduled start times of construction processes, transport processes and warehouse processes as well as resources scheduled for the processes. The simulation ensures that the components will only be delivered if they can be stored or installed directly. The simulated process times of the assembly processes are entered into a table during the simulation run, so that the duration of the individual construction processes and the total duration of the project can be estimated. An animation of the processes illustrates the approximate sequence of logistics processes on the construction site.

To evaluate the planning scenario, in addition to the simulated process times, key performance indicators, such as the utilization of resources (in percent) or the utilization of storage areas (in storage units) are calculated over the entire duration of the simulated project. The simulation-based validation provides a consistent and valid logistics model that can also be used to control logistics on the construction site. In case 1, the simulation points out that the crane, the crane operator, and the employee are almost always working at 100% capacity at the beginning of the simulated time (see Figure 9). This indicates that a new scenario with a second crane could lead to a better utilization of resources and personnel. Therefore, this scenario with two cranes is also being tested in a simulation study. The use of two cranes for Case 1 leads to a reduction of the simulated project time. However, this scenario is not regarded to be economical.

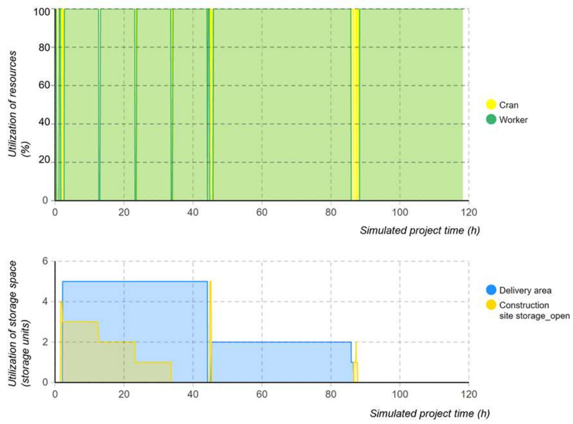

Figure 9. Utilization of resources (%) and utilization of storage space (storage units)

In the first scenario with one crane, the simulation carried out shows the utilization of the storage areas as an example. At the beginning of the construction processes the delivery area is highly utilized and the construction site storage (open storage) only stores a few parts over simulated project time (max. five storage units). Thus, the simulation provides the requirements for dimensioning of storage areas on the construction site (see Figure 9).

6 Conclusion & Outlook

Our approach demonstrates that creating step-by-step instructions for IFC files from any source works very well even at this early stage. The main effort lies in the categorization of the elements. Depending on the source of the IFC file, this can be greatly simplified and thus accelerated by using regular expressions. However, regular expressions can only be used across projects for models in which elements of the same type also have a similar name. Therefore, it is very important that the models or their elements are always classified in the same way. If a uniform classification is not available, a manual revision based on given guidelines must be carried out. To avoid this problem, interfaces to different modeling tools must be developed. These interfaces could be designed in such a way that they provide more information than the respective IFC export function provides. In addition, this also eliminates the need to create a collision database, since the links between components can usually be determined directly by the design software. This is particularly advantageous for components with a more complex geometry, such as angled pipe connections or reinforcement meshes. Bidirectional communication is also conceivable. With a sufficient number of previous design projects and thus maintenance of the ontology as well as regular expressions it will be possible to generate the design instruction with a single click. In addition to the application for simulation, cost estimation [3] is also possible.

To evaluate our methodology in terms of its practical applicability, we have presented it to seven experts from the industry. The experts are representatives of companies from the fields of plant construction and logistics. They agree that detailed digital construction site logistics planning is of high importance or is becoming increasingly important. The participants in the evaluation survey are convinced that enriching the BIM model with information on construction site logistics will offer their companies advantages in future in the exchange between company departments and project partners. In their opinion, this information should also be available in digital form directly on the construction site. The semi-automatic generation of step-by-step construction instructions is less or not important for two in seven participants in the evaluation survey, while five in seven rate it as important or very important. However, all respondents agree that semi-automatic generation of schedules is very helpful for their companies.

The high potential lies in the iterative construction process and construction logistics planning which is made possible by our methodology. This iterative planning requires that the current state of construction is known accurately at all times. There are already many established possibilities for this today, by means of automated continuous construction progress monitoring [9]. As soon as an interface for communication with the simulation tool has been developed, it is possible to generate the simulation model semi-automatically. In the end, a decision maker will still make the final choice for the preferred scenario. In this way, in case of delays due to bad weather or delayed deliveries, damaged material etc., alternative strategies can be developed in a short time and with little manpower, which ensures an efficient construction process despite the disruption and also minimizes otherwise occurring delays in the best possible way.

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