CIB World Building Congress 2019
Hong Kong SAR, China
17 – 21 June 2019

Smart Factory Adaptation Planning by means of BIM in Combination of Constraint Solving Techniques

Lisa Theresa Lenz,
Chair of Construction Management, Department of Architecture and Civil Engineering, TU Dortmund University
(email: lisa.lenz@tu-dortmund.de)
Julian Graefenstein,
Chair of Enterprise Logistics, Department of Mechanical Engineering, TU Dortmund University
(email: graefenstein@lfo.tu-dortmund.de)
Jan Winkels,
Chair for Software Engineering, Department of Computer Science, TU Dortmund University
(email: jan.winkels@tu-dortmund.de)
Mike Gralla,
Chair of Construction Management, Department of Architecture and Civil Engineering, TU Dortmund University
(email: mike.gralla@tu-dortmund.de)

Abstract

Current environmental changes according global economic activities and the affected companies with a special focus on produced goods lead to a stronger need of the ability to deal with arising dynamics and complexity. In order to be able to remain competitive in this environment, producing companies have to adapt to these dynamics and the accompanied needs for changes of the production system in particular. Therefore, the process of adaptation, from a very small adjustment of a production cell in between the production system to the whole factory system with all corresponding elements, has to be as short and effective as possible. The aforementioned dynamics bring a need for more and more adaptations in less time with it and in combination with the accompanied complexity the difficulty of these adaptations is rising. A dilemma emerges when the given time and budget is in contrast to the necessary amount of resources for the needed adaptation. As it comes clear there is a major problem in solving this dilemma by using existing approaches for factory planning. Especially the highly interdisciplinary research field of factory planning is very dynamic and complex itself. There is a gap between the field of production planning and the realization of the planned system in form of a factory object. At some point the planning team finishes the task-oriented planning phase and hands over the results to the construction management. At this point there is a gap in approaches that manage the interfaces between the planning phase of the production system itself and the planning phase of the necessary factory building adaptations by the construction management team in a factory planning project. In this paper we address this gap by providing an approach to automatically supply preprocessed information in order to speed up the decision process and the subsequent realization phase by creating a schedule for the realization of the adaptation. Therefore we use an exemplary scenario in which the approach is used to replace a part of an assembly line with robots. It is shown that the approach is able to transfer the results of the planning phase into the schedule for the realization and that thereby the realization phase can be raised to a higher level of adaptation intelligence by orchestrating specific tasks automatically through constraint-solving methods.

Keywords: Adaptation Intelligence, Building Information Modeling, Constraint Solving Techniques, Factory Adaptation Planning, Modular Planning

1. Requirements on Factory Adaptation Planning

Besides environmental changes, such as faster changing customer needs, new laws regarding a more ecological footprint of products and production, there are other more specific drivers concerning a producing company that influence the need for more dynamic and complex adaptations of the whole factory system. Developments in technology addressing not only the final product itself but also the shop floor and all its elements like the machines, e.g. 3D printers, supporting tools such as AR glasses and new materials that can be used for the building itself shorten the time span of necessary adaptation activities (Schuh, 2005). Considering that technology develops faster and becomes more and more complex, the people that are experts in these technological advancements are more and more from very different disciplines. This interdisciplinarity in adaptation projects needs to be managed not only by rising transparency in the planning process but also by using an holistic digital planning model on which every participant of the project can work and which can be used for communication along all disciplines. Efficient management of such a complex planning project is crucial for a successful adaptation. The usage of a holistic planning model for documentation, communication, interaction and to actual plan the realization can be an important tool. However, not only a holistic planning model is necessary to be as efficient as possible in an adaptation project. Focusing on the planning phase of the adaptation process it is also necessary to have a planning method that guides the participants through the whole planning process.

2. Interdependencies and Challenges for the Adaptation Planning Team

Along a factory planning project there are several experts participating in some parts of the planning and realization tasks (see Fig. 1). These participants form individual and interdisciplinary planning teams according to the specific planning project. Several interdisciplinary teams work on specific tasks in between the whole planning process and generate information which is then needed by other teams at a specific point of planning. The management of interchanging information and guiding the experts along the whole project is a very elaborate but also very important part in the field of factory planning. Several classical approaches in the research field of factory planning focus on a sequential and phase oriented planning process. These phases consist of specific planning tasks, which have to be worked out and completed in special teams in order to move on to the next phase (Aggteleky, 1987: 31f.; Grundig, 2015: 37; Kettner, Schmidt and Greim, 1984: 11f).

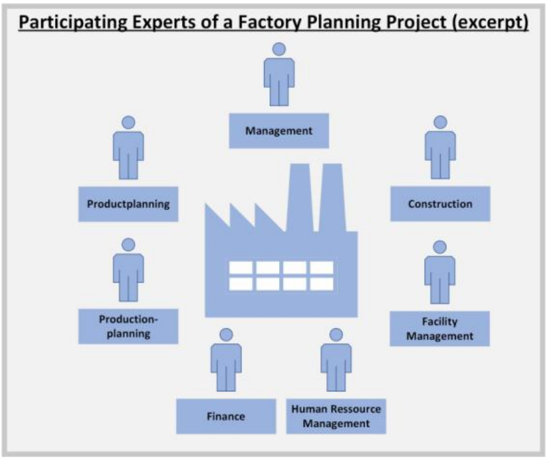

Figure 1: Participating experts of a factory planning project (excerpt)

Those approaches are not suitable for a quick and effective response to the aforementioned changes as they are not flexible in their processing and cannot be individually orchestrated according to the individual planning project (Schuh, Kampker and Wesch-Potente, 2011: 89ff). More flexible and adjustable approaches are needed in order to react to changes during the planning process very quickly (Graefenstein *et al.*, 2018: 157ff; Nöcker, 2012: 6f.). Some approaches address these requirements and focus on a modular way of orchestrating a planning process by formulating several planning tasks into specific planning modules (Burggräf, 2013: 100ff; Nöcker, 2012: 77ff). These modules can be arranged according to the individual planning project and be adjusted very quickly if necessary. Only few approaches address the interdisciplinarity of a factory planning project (Kampker *et al.*, 2011: 111ff). The guideline 5200 for factory planning by the Association of German Engineers (VDI) is a classic approach that consists of 7 planning phases, beginning with the setting of objectives and ending the last phase the ramp-up support. It considers tasks from the German Scale of Fees for Services by Architects and Engineers (HOAI) and assigns the 9 HOAI services phases to corresponding planning phases of the VDI guideline 5200 (Verein deutscher Ingenieure e.V., 2011: 1ff). This approach just highlights the phases in the planning process, in which knowhow by a construction management team is needed and how they are connected into the planning process. Another approach focuses on the coordination of several experts in the planning process based on a modular approach. By using existing planning modules and extending them by specific construction management modules a more detailed coordination of tasks, experts and used information is possible (Meckelnborg, 2015: 49ff).

The approach in this paper also uses planning modules but generates the planning process automatically with the help of constraint solving methods (Graefenstein *et al.*, 2017: 209ff). These modules, which represents specific planning tasks, have defined in- and outputs. These in- and outputs define the interconnection between each module and therefore can be used to orchestrate these modules automatically. To start with the automatic orchestration of an individual factory planning process the target has to be defined. The next steps are to look up which inputs are needed to generate the needed output, identify the module that generates these inputs as outputs and place them in front of the module that needs the input. This process continues till the module is found that has every input it needs. The result is a whole planning process for the individual project that can be worked on. These modules can also be used to automatically generate a time line for the whole project in form of a network diagram. It was also shown that this constraint-solving based approach can be used to find suitable solutions in the very first phase of planning by setting objectives for the project. In this case, the approach was used to find objects that provide a certain set abilities that match with the overall goal of wanted performance (Winkels et al*.*, 2018: 487ff).

The approach will be used in this paper to orchestrate a time schedule for the installation of an industry robot that will replace a manual workplaces. In addition to that the already generated information in the production planning phase for a specific robot replacement will be used in a BIM environment. This will highlight the integration of information from an early planning stage which can be transferred and used for construction management.

2.1 Factory Planning

During a factory planning project several objectives have to be reached. Based on information which is already available and results which have to be generated in the planning process the existing factory system has to be adapted. The decisions made during this process do not always affect the building directly by changing several parts of the factory. In some cases only parts considering the connections of technical equipment or the payload has to be changed in a specific part of the factory for new machinery are affected. The decisions for changing a production line for example and therefore parts of the machinery used are made at an early stage of the planning process.

The corresponding information to these changes, which will affect the factory building, is handed over at a later stage of the planning process. Unfortunately it occurs that this information which is necessary for the construction management team will not be considered by the production planning team and therefore has to be worked on by the construction team additionally. This process could be circumvented by directly adding the information for the construction management team in the early planning stage. Therefore it is helpful to directly connect information to an integrated model that is worked on in parallel to the planning process. Especially for the use in the realization phase of a factory planning project it would be not only helpful and time saving but would also prevent mistakes at an early stage of planning which otherwise have to be fixed later on.

2.2 Construction Management

If an adaptation of the production system is required, an evaluation of the possible influences on the existing building with consideration towards its flexibility and possible needed structural adaptation is necessary at the same time. This is exemplified by the determination of the actual condition of a factory building. The examination of the documentation of the building is time-consuming due to the number of documents as well as their inhomogeneity in the form of different formats and the lack of relation of the information to each other. This also involves all kinds of risks, such as incorrect and incomplete data acquisition. A further elementary factor is the often outdated status of the documents, which make inspections or even the recording of the building in its actual state using laser scanning techniques indispensable (see Fig. 2).

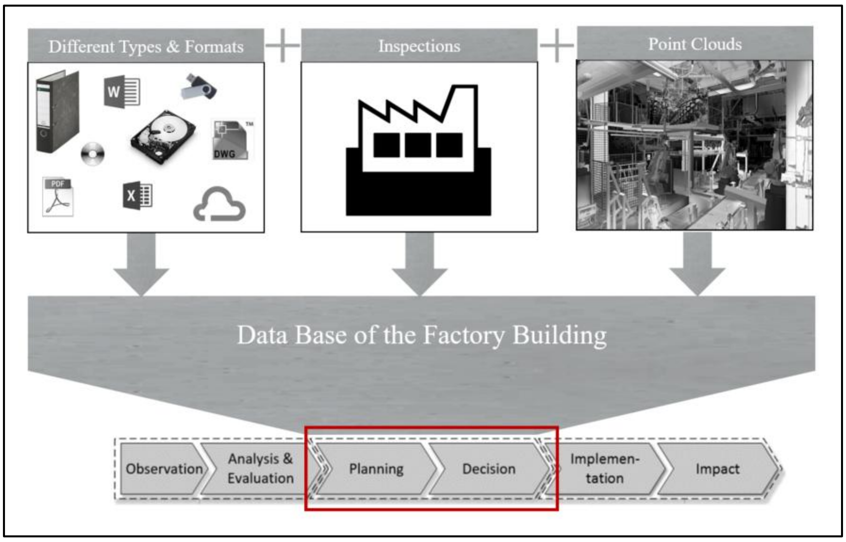

Figure 2: Data collection & base of the factory building as input for the adaptation process (Kuhn et al. 2011; Nyhuis et al. 2008; Hildebrand et al. 2003; Hernandez Morales 2003)

By considering necessary construction adaptations as well as conventional construction planning processes in the context of the factory adaptation process, standard methods are unable to support the process in a fast and efficient way. By application of the BIM method a Building Information Model, which contains all the needed information in one database is generated.

Building Information Modeling (BIM) is a method in the construction industry that includes the generation and management of digital representations of physical and functional characteristics of a building. (Egger et al. 2013: 18) As figure 3 illustrates the BIM method is separated from conventional planning methods at the point from planning in three dimensions combined with other information e.g. data like quality information or maximum loads. At this stage it turns from a building model to a building information model, where information about time and costs are associated into the fourth and fifth dimension. (Gralla, Lenz 2017: 210)

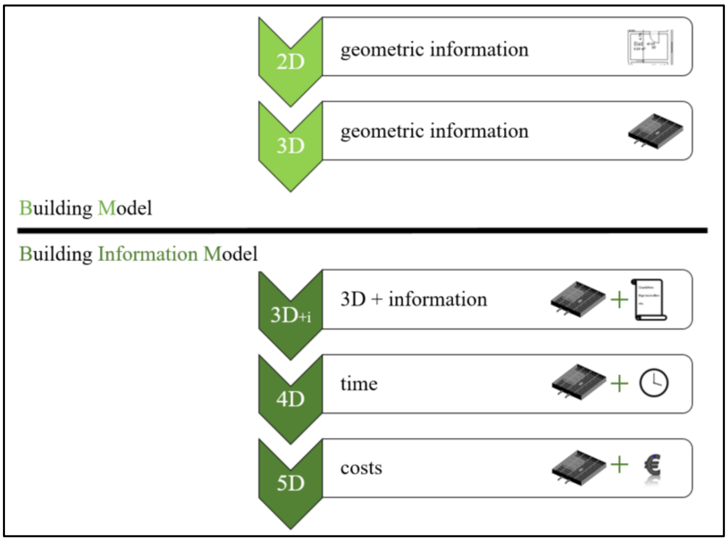

Figure 3: Building Information Modeling vs. conventional planning (Gralla, Lenz 2017: 210)

Building information models represent a database that provides a reliable knowledge base for example evaluation purposes throughout a building´s life cycle – from initial planning to demolition. Using the BIM method also offers the ability to optimize processes related to the life cycle of a factory building, such as supporting factory adaptation process and making them more efficient and faster. (Delbrügger, et al. 2017: 1)

Since that modules are available within the context of factory planning for considering the effects of adaptation modifications on the factory building (construction and technical building equipment), it is obvious to combine the approach of the planning modules and the BIM-method.

3. Use Case: Subsequent Assembly of an Industrial Robot

In order to identify the possibilities and benefits of combining different stakeholders in a factory adaptation planning process, the use case of replacing a manual work process by a robot is investigated. For that purpose it is necessary to analyze different phases in a specific way in order to be able to determine the requirements for the necessary database. For this the database of possible necessary factory building adaptation in a worst case scenario is developed and combined within the factory planning modules to see which interdependencies between the disciplines can be identified and how constraint solving techniques can be used to automatically generate scheduling variants.

The necessary database for the use case consists of:

- the data of the production technology (robot) to be implemented in four different variants,

Table 1: data overview production machine in different variants

scenario #	name scenario	system	subsystem	# building part	name building part	building part ID	parameter	value
1	production machine	Kuka KR 30	supply of the machine	2	factory area	electrical supply	installed load	4,0 kVA
1	production machine	Kuka KR 30	supply of the machine	2	factory area	electrical supply	protection class	IP 65
1	production machine	Kuka KR 30	networking of the machines	2	factory area	data supply	# of data supplies	1
1	production machine	Kuka KR 30	networking of the machines	2	factory area	wireless lan	wireless lan available	no
1	production machine	Kuka KR 30	supply of the machine	2	factory area	compressed air supply	compressed air supply necessary	no
1	production machine	Kuka KR 30	fastening of machines	4	foundation area	fastening system	anchor diameter	18 mm
1	production machine	Kuka KR 30	fastening of machines	4	foundation area	fastening system	anchor embedment depth	125 mm
1	production machine	Kuka KR 30	environment of the machines	2	factory area	heating / air-conditioning	maximum temperature	55 °C

- the data of the factory building parts, which will possibly be influenced differentiated in qualities, costs and time consumption for the adaptation,
- the data of the factory planning modules (see chapter 2.1)
- and the interfaces and dependencies (in- and output) between the different data types (see Fig. 4).

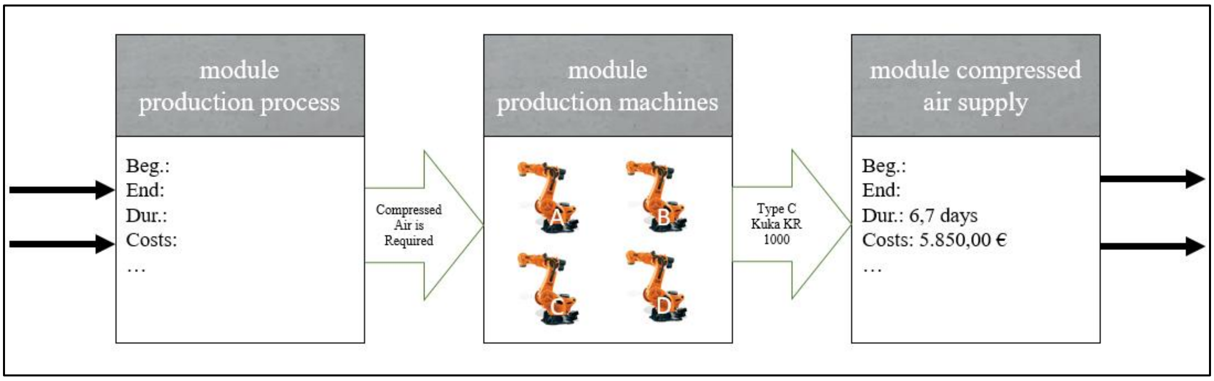

Figure 4: symbiosis of interdisciplinary data structures using the example of the production requirement compressed air supply

This illustrates that there is a high potential in the application of cross-system data composition of for example BIM-data with other relevant systems, like the planning modules in this case to identify interfaces and dependencies between different stakeholders and to evaluate decisions among the entire adaptation process in factory planning. (Gralla, Lenz 2018: 12) The main focus in this case is on the preparation phase by using the interdisciplinary data systems (factory planning modules and Building Information Modeling) for improving the speed and efficiency of the planning and decision processes in factory adaptation planning (see Fig. 5).

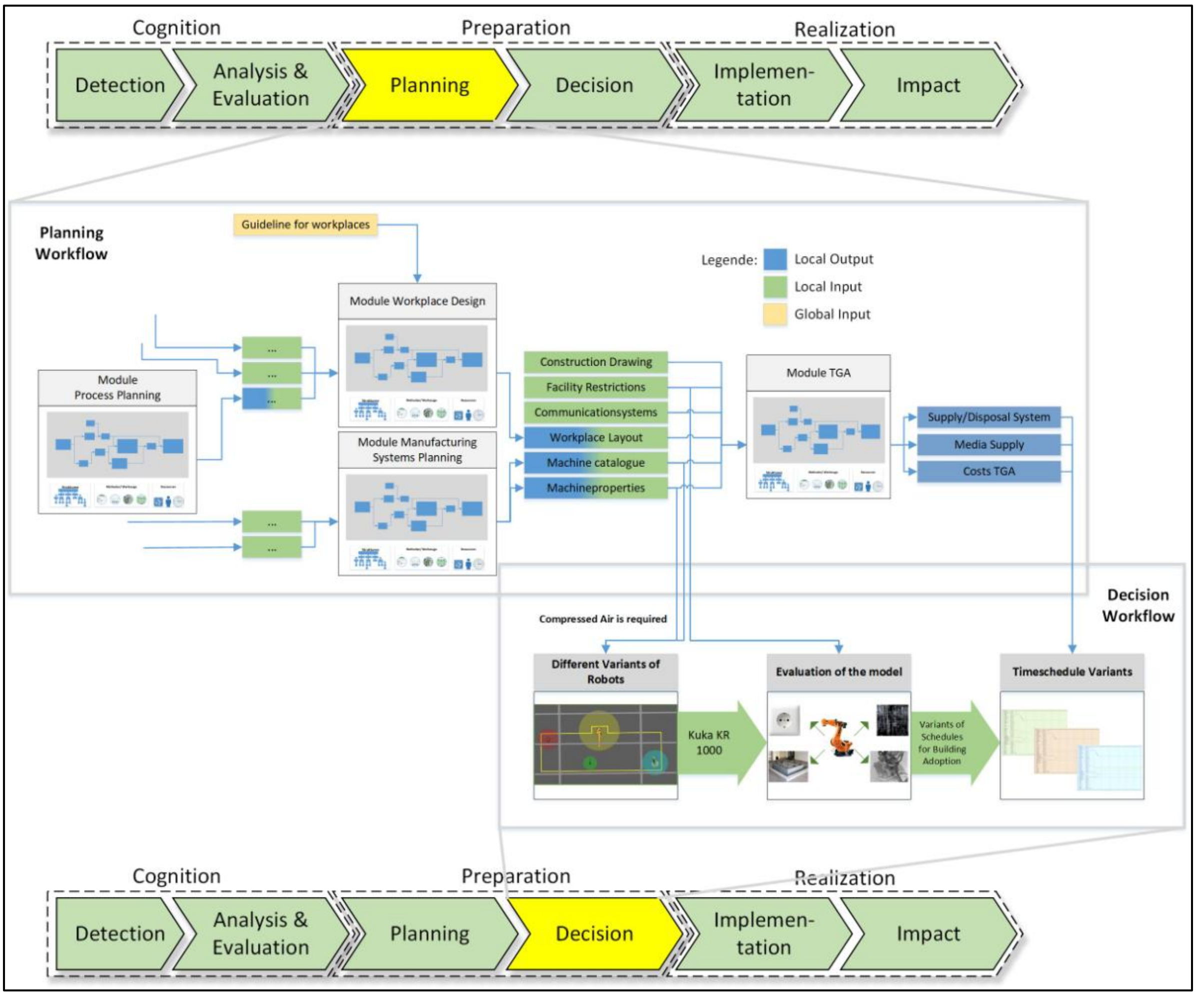

Figure 5: Combination of planning and decision workflow regarding BIM (Kuka Robot; Kuhn et al. 2011; Nyhuis et al. 2008; Hildebrand et al. 2003; Hernandez Morales 2003)

4. Implementation

The modular approach of planning presented in the previous section now requires a technology that allows the orchestration of the modules to be carried out automatically. For this case, we use techniques of constraint solving as well as combinatorial logic.

This section explains the concept of the constraint solving problem (or constraint satisfaction problem, CSP for short). The aim of this problem is to find a solution for a specific problem that meets all its preconditions. The solution is usually a specific assignment of target variables to certain values. Constrains are the conditions and restrictions that apply to these variables. These can be, for example, predetermined value ranges, but also relationships to other variables. For example, for two target variables x and y, the constraint set $\{x + y = 5, x > 1, y > 1, x > y\}$ is given. Using constraint-solving methods, the target occupancy $x = 3$ and $y = 2$ can be calculated from this, which fulfills all given conditions. In this example, this is the only solution. In many cases, however, it is also conceivable that several solutions to a problem exist. In contrast to other heuristics or optimization methods, apart from the question of whether the solution satisfies all constraints, no further statements on solution quality are made. The aim is not to find the best possible solution, but rather to determine whether there is even a solution under the existing restrictions. If this is not the case, then the constraints are contradictory. Software is already available for the computer-aided solution of such problems. For the approach used here, we used the constraint solver "Z3" from the Microsoft Research Group (de Moura et al. 2008)

To use this technique for the orchestration of individual planning modules, it is embedded in a recursive procedure based on combinatory logic. The technique is implemented in a tool called Combinatory Logic Synthesizer (CLS) (Bessai et a. 2014), developed by the Chair for Software Engineering at the Department of Computer Science at the TU Dortmund University[1] and was used for factory planning purposes before (Winkels et al. 2018). In the implemented procedure, a module is interpreted as a function. Each module has specific inputs and outputs. To process (or execute) a module, all required inputs of this module must be present. The existence of the data inputs can again be modeled as a constraint and can be done either via a Boolean variable or via concrete metric values. This can be adapted to a function, which has arguments (inputs) and return values (outputs). So for example the module production process (as seen in Figure 4) requires an air supply system and a list of possible production machines and provides a certain instance of a possible Production Process. Therefore the module is represented by the function (Compressed Air System -> Production Machine (a)) -> Production Process). It should be noted that the function does not require a specific machine, but a module with the Type Production Machine as an input. Therefore every suitable machine can be used.

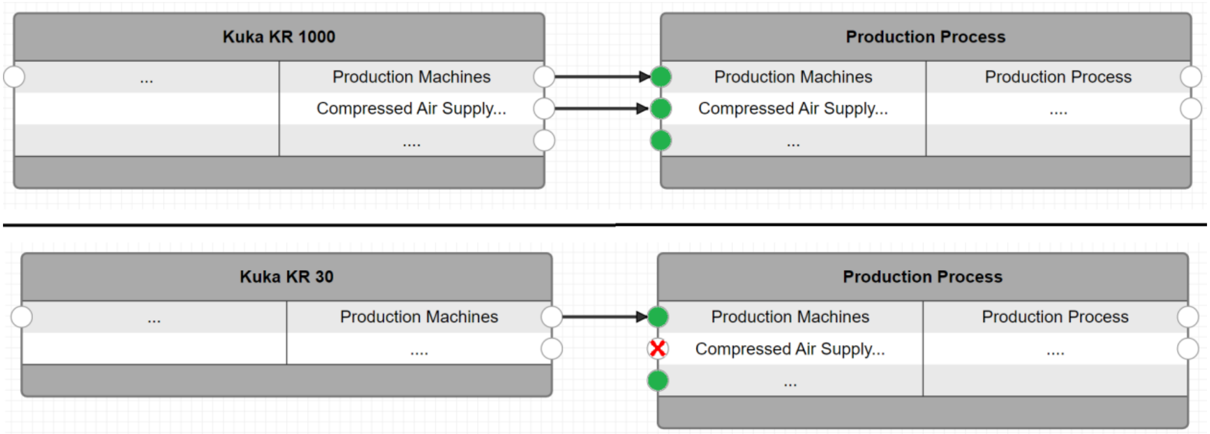

Figure 6: Example of orchestrated modules and different solutions

[1] The CLS is available at https://www.combinators.org

If a module is to be used in a workflow, it can be checked by means of constraint solving, whether this module is ready for processing, i.e. whether all prerequisites for processing this module are fulfilled. In the tool, the user determines a target for the calculation of which a sequence is to be generated. After the user has specified this target size, a module is determined that can realize this target size as output. The next step is to check whether the inputs of this module are in the database of the system and if this enables the module to generate a solution. This is done by inserting each candidate module of the appropriate type into the module function of the module currently being tested. Thus arise several instances of a process, each with different properties. Thus, in the above example, a new process instance is created for each available Kuka Robot machine. It then checks whether the properties of the machine used in the respective instance match the constraints of the overall process and the previous module. In Figure 6, it can be seen that only the Kuka KR 1000 has a compress air supply system and therefore its process instance is the one to be used. The Kuka KR 30 variant will be discarded and removed from the list of possible solutions. If no solution can be found, it is determined by stepping out individual constraints from the constraint set which condition leads to the unacceptability of the problem. This means trying to compute a solution while ignoring one constraint at a time. This can be used to derive which constraints justify the unfulfillability of the original problem with a complete set of constraints. In this way, it can be determined which input data of a module is missing in the database of the system (for example a specific type of a machine). These missing data are then considered as new module targets for which the procedure is repeated. Thus, suitable modules are again determined and the non-detachable input constraint of the original module is replaced by the input constraints of the newly determined module. Again an attempt is made to find a solution under the now extended constraint set. The procedure runs until a solution has been found, so all inputs are completely covered by the database. This would correspond to a suitable starting point for a processing course. If the constraints of a module cannot be resolved in the course of the procedure, then this shows that no processing sequence can be generated from the existing information in the database. In this case, it is not possible to deduce from the available modules a constraint quantity for which a solution can be generated, which necessitates intervention by the user. It can either remove constraints from the constraint set of the problem on its own to create a solution, or manually enter missing or unpredictable data.

5. Outlook

In this paper, we showed how automated, modular planning works in conjunction with the BIM method. It became clear that the interdisciplinary cooperation and the use of technologies from various disciplines such as factory planning, computer science and civil engineering can provide a tool for the systematic support of planning tasks.

Overall, it can be stated that the use of constraint solvers can be described as a promising approach for the configuration of planning processes. The described methodology allows the data link of individual planning tasks or modules to comprehensive planning process chains. In the course of the current developments in the field of modularization of planning processes, the procedure thus represents a necessary IT-technical implementation possibility for process structuring and semi-automatic planning process configuration. In addition to the acceleration of the planning process, the potential lies in an increase in process transparency, which is achieved by focusing on the for the respective planning project necessary planning content. In addition, a kind of planning assistance is created, which, for example, also supports small and medium-sized companies with little or no planning expertise in the rough planning and coordination of planning projects.

This approach is to be expanded in the future. In addition to the generation of decision variants in a planning workflow that has been realized up to now, the automated validation of the same is to be in the foreground in the future. It is conceivable to connect the existing software to virtual testbeds and simulation software in order to automatically simulate and evaluate any variants.

Acknowledgements

The authors would like to acknowledge the support by the DFG Deutsche Forschungsgemeinschaft for the Research Training Group 2193 Adaptation Intelligence of Factories in a Dynamic and Complex Environment.

References

Aggteleky, B. (1987): Fabrikplanung: Werksentwicklung und Betriebsrationalisierung. 2nd edn. Hanser, München.

Bessai, J.; Dudenhefner, A.; Düdder, B.; Martens, M.; Rehof, J. (2014): Combinatory Logic Synthesizer, Margaria, T.; Steffen, B. (eds.) Leveraging Applications of Formal Methods, Verification and Validation. Technologies for Mastering Change. ISoLA 2014. Lecture Notes in Computer Science, vol 8802. Springer, Berlin, Heidelberg.

Delbrügger, T.; Lenz, L.; Losch, D.; Roßmann, J. (2017): A Navigation Framework for Digital Twins of Factories based on Building Information Modeling, 22nd International Conference of Emerging Technologies and Factory Automation ETFA, 2017, Cyprus, pp. 1-4.

Egger, M.; Hausknecht, K.; Liebich, T.; Pryzybylo, J. (2013): BIM Leitfaden für Deutschland, Information und Ratgeber, Endbericht, ZukunftBAU, München.

Graefenstein, J.; Scholz, D.; Henke, M.; Winkels, J.; Rehof, J. (2017): Intelligente Orchestrierung von Planungsprozessen: Anwendung von logikbasiertem Constraintsolving in der Fabrikplanung, ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, 112(4), pp. 209–213.

Graefenstein, J.; Scholz, D.; Seifert, O.; Winkels, J.; Henke, M.; Rehof, J. (2018): Automated Processing of Planning Modules in Factory Planning by Means of Constraint Solving Using the Example of Production Segmentation, in Hankammer, S. et al. (eds.) Customization 4.0: Proceedings of the 9th world mass customization & personalization, Springer International Publishing, Cham, pp. 157–172.

Gralla, M.; Lenz, L. (2017): Digitalisierung im Baubetrieb – Building Information Modeling und virtuelle Zwillinge, Festschrift für Prof. Motzko, Jörg Fenner (ed.), Technische Universität Darmstadt, p. 210.

Gralla, M.; Lenz, L. (2018): Datenkomposition im Spezialtiefbau mit BIM, Methodik – Ziele – Potenziale. In: Schanz, T. (ed.) Beiträge zum RuhrGeo Tag 2018, Innovationen im Spezialtiefbau und in der Umweltgeotechnik. Schriftenreihe des Lehrstuhls für Grundbau, Boden- und Felsmechanik. Ruhr-Universität Bochum, p. 12.

Grundig, C.-G. (2015): Fabrikplanung: Planungssystematik - Methoden - Anwendungen. 5th edn. Hanser, München.

Hernandez, Morales, R. (2003): Systematik der Wandlungsfähigkeit in der Fabrikplanung, VDI-Verlag, Düsseldorf.

Hildebrand, T.; Mäding, K.; Günther, U. (2005): PLUG + PRODUCE. HBF – Institut für Betriebswissenschaften und Fabriksysteme, Technische Universität Chemnitz.

Kampker, A.; Meckelnborg, A.; Deutskens, C.; Frombach, R.; Grefrath, C. (2011): Synchrone Fabrikplanung, ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, 106(3), pp. 111–114.

Kettner, H.; Schmidt, J.; Greim, H.-R. (1984): Leitfaden der systematischen Fabrikplanung. Hanser, München.

Kuhn, A.; Klingebiel, K.; Schmidt, A.; Luft, N. (2011): Modellgestütztes Planen und kollaboratives Experimentieren für robuste Distributionssysteme. Spath, D. (ed.): Wissensarbeit – zwischen strengen Prozessen und kreativem Spielraum. GITO-Verlag (Schriftenreihe der Hochschulgruppe für Arbeits- und Betriebsorganisationen e. V. (HAB), 24.), Berlin , pp. 177 – 198.

Kuka Robot [Online]. Available at: https://www.logismarket.at/kuka-roboter-cee-gmbh/industrieroboter-3/1980108196-1072176582-p.html (Accessed: 07.02.2019).

Meckelnborg, A. (2015): Integrative Fabrikplanung durch effiziente Koordinationsmodelle. Aachen, Technische Hochschule, Dissertation, 2015, Apprimus-Verlag, Aachen.

de Moura L.; Bjørner N. (2008): Z3: An Efficient SMT Solver. Ramakrishnan C. R., Rehof J. (eds.) Tools and Algorithms for the Construction and Analysis of Systems. TACAS 2008. Lecture Notes in Computer Science, vol. 4963. Springer, Berlin, Heidelberg.

Nöcker, J.C. (2012): Zustandsbasierte Fabrikplanung. Aachen, Technische Hochschule, Dissertation, 2012, Apprimus-Verlag, Aachen.

Nyhuis, P.; Reinhardt, G.; Abele, E. (2008): Wandlungsfähige Produktionssysteme, Heute die Industrie von morgen gestalten: PZH Produktionstechnisches Zentrum GmbH, Report, (2008), p. 1 – 168.

Schuh, G. (2005) 'Fabrikplanung in Zeiten der Globalisierung', wt Werkstatttechnik online, 95(4), p. 174.

Schuh, G.; Kampker, A.; Wesch-Potente, C. (2011): Condition based factory planning, Production Engineering, 5(1), pp. 89–94.

Verein Deutscher Ingenieure e.V. (2011): Fabrikplanung - Planungsvorgehen. Beuth, Berlin.

Winkels J.; Graefenstein J.; Schäfer T.; Scholz D.; Rehof J.; Henke M. (2018): Automatic Composition of Rough Solution Possibilities in the Target Planning of Factory Planning Projects by Means of Combinatory Logic. In: Margaria T., Steffen B. (eds.) Leveraging Applications of Formal Methods, Verification and Validation. Industrial Practice. ISoLA 2018. Lecture Notes in Computer Science, vol 11247. Springer, Cham.