SYSTEMATIC MERGING OF BUILDING INFORMATION AND SIMULATION MODELS FOR THE AUTOMATED EVALUATION OF FACTORY LAYOUT VARIANTS

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Abstract

The turbulent business environment facing manufacturing companies today has prompted the need for a more efficient decision making process in the factory planning without compromising on reliability. Additional, emerging objectives, e.g., demand for ecological sustainability and adaptability, also present challenges that must be addressed. This paper describes a systematical integration approach for Building Information Modeling and simulation data to streamline the planning process by automatically evaluate factory layout variants. An experiment has been conducted to demonstrate the viability of the approach.

Introduction

The business environment of manufacturing companies is becoming increasingly turbulent (Wiendahl et al. 2014) due to circumstances like shortening product life cycles, climate change, and global political uncertainties. The response time and adaptability of their production facilities play a critical role for these companies to remain competitive (Abele und Reinhart 2011; Schäfer et al. 2022; Delbrügger et al. 2017). Thus, factory planning projects become more dynamic, with an increased demand for more efficient information exchange. Communication is mostly bilateral, but the right data is not always available to all stakeholders at the time it is needed (Wiendahl et al. 2001). Innovative planning techniques utilizing digital collaboration are considered pertinent to address these challenges.

Building Information Modeling (BIM) has become an established collaboration method in the construction industry. This has also transferred to factory planning approaches (Neuhäuser et al. 2021a; Neuhäuser et al. 2022; Schäfer et al. 2022; Rieke et al. 2021; Winkels et al. 2020; Ebade Esfahani 2022) and is perceived as very relevant (Neuhäuser et al. 2023). Collaboration with BIM is based on digital partial models that are regularly merged into the federated model, i.e., a single source of truth of the factory (BMVI 2015; Rieke et al. 2021). However, BIM models only represent static data. As the production is a dynamic system, it is assessed using simulation models during planning (VDI 4499-1). The results of the simulations must then be fed back into the BIM model, particularly with respect to the production layout, which is mainly done manually at present.

The layout planning procedure is considered the most variant-rich and highly complex task in the factory planning (Rist 2008), and is therefore associated with a high manual effort. Furthermore, an effective layout has a considerable impact on the future performance of a production system, particularly with respect to the flow systems, e.g., material and energy flows (Schenk et al. 2014). In this context, the material flows can account to approximately 30 % of a factory's operating costs (Hawer et al. 2015).

Today's turbulent environment for manufacturing business has created more demand and introduced new objectives for factory planning, e.g., ecological sustainability and adaptability. These new objectives have led to more evaluation criteria for layout variants (Schäfer et al. 2022) that also results in increased complexity as well as manual effort. Simultaneously, there is a demand for increased efficiency in choosing the optimum layout variant with no compromise for reliability and performance. Therefore, automated approaches that can evaluate layout variants efficiently and effectively are needed. Thus, the main research question is:

How can the evaluation of factory layout variants be performed more efficiently to enable fast and reliable decision-making using ACABIM (Automated Compliance Audit of Building Information Models)?

The aim of this paper is to present an approach to systematically integrate data from BIM and simulation models in a digital environment to support automated evaluation criteria for layout variants. The software platform ACABIM is used as integration tool in an experiment.

The paper is structured as follows: First, the most important theoretical fundamentals and the state of the art are discussed. Second, a use case is presented to test the approach using ACABIM. Third, the results are analyzed, discussed, and summarized. Finally, an outlook on further research is given.

Fundamentals and State of the Art

Factory Planning

A factory is a place where goods are produced in value creating processes in a production system typically enclosed within a building. The planning of a factory is a systematic and objective-oriented process that is structured into a sequence of phases. The concept planning phase involves both ideal and real layout planning and typically utilizes block layouts represented by bounding boxes. During ideal planning, structural units of the factory are arranged for the optimal material flow without considering restrictions, e.g., constraints imposed by building structures. Then, the ideal layout is adapted to existing physical constraints during the real layout planning process. The real layout planning includes the development of different variants, which are assessed and the best one chosen for subsequent detailed planning. (VDI 5200-1; Wiendahl et al. 2014)

Specific methods, models, and tools are necessary to evaluate planning variants. The Digital Factory is established as a response.

Digital Factory

The Digital Factory is a network of digital models, methods, and tools (e.g., simulations), which are integrated by a continuous data management system. The aim of the Digital Factory is the holistic planning, evaluation, and ongoing improvement of factories. Thus, the Digital Factory is used to optimize the production system in factory planning projects. BIM has been shown to be useful in the factory building planning (Wiendahl et al. 2014). (VDI 4499-1)

BIM

BIM is a collaborative methodology based on digital models of an asset, which is used over its whole life cycle (VDI 2552-2; DIN EN ISO 19650-1). In terms of data exchange, a distinction can be made between Open- and Closed-BIM approaches. A project participant may choose different supporting BIM software tools in the Open-BIM approach, while only the software of one specific supplier can be used in the Closed-BIM approach. The Open-BIM approach exchanges data using open standard formats such as the ISO-standard Industry Foundation Classes (IFC). In the Closed-BIM approach, only proprietary data formats of specific software suppliers are supported. (Borrmann et al. 2015)

While the application of the Digital Factory in factory planning processes is already a state of the art, the use of BIM in the digital factory planning is emerging research (Gralla und Weist 2021). Several approaches have been suggested to establish BIM in factory planning since 2018.

BIM and Digital Factory Planning

(Ebade Esfahani 2022; Burggräf et al. 2019; Burggräf et al. 2021; Burggräf et al. 2020) explained general classifications of BIM-specific concepts like the Level of Development (LoD), efficient data management, or automatic design validation system between the planning of production systems and that of mechanical, electrical, and plumbing (MEP). (Rieke et al. 2021) and (Schäfer et al. 2022) deepened the project organization approaches by describing LoD in factory planning more specifically. They presented organization charts for the collaboration between production system and building planning, which are generalized out of a real- world factory planning projects. Moreover, (Schäfer et al. 2022) stated that the parameterization of BIM-Models regarding factory objectives like ecological sustainability or adaptability is a promising approach for future research. (Süße und Putz 2021; Süße et al. 2022) as well as (Süße et al. 2022) introduced a general framework for generative layout design in factory layout planning. Thereby, they dwelled on ecological objectives with the BIM model as the data source. (Lampe and Böck 2022) and (Dallasega et al. 2020) use this data source to empower augmented and virtual reality applications. An integration of the BIM model and simulation tools or results are not given. (Eriksson et al. (2018) and (Hellmuth et al. 2020) focused on the automated generation and update of BIM models via point clouds and photogrammetry. Moreover, the research training group “Adaption intelligence of Factories in a Dynamic and Complex Environment” focused on the evaluation of factory building adaptions due to changes in the production system. The evaluation approaches described in (Lenz 2019; Winkels et al. 2020; Lenz et al. 2019b; Lenz et al. 2019a; Weist und Lenz 2019) use Constraint Solving Techniques to assess the impacts of production changes, e.g., the integration of robots in factory buildings.

Although these approaches address the research field between digital factory planning and BIM, no approach has been developed to systematically integrate BIM and simulation models and to automatically evaluate layout variants. This research gap shall be closed by using the workflow-driven approach in conjunction with ACABIM, a commercial software tool (Amor und Dimyadi 2021).

ACABIM

ACABIM is an open standard digital platform for auditing building designs and managing assets with a compliance focus. It employs a workflow-driven approach to human-guided automation and supports BPMN-compliant workflow models (DIN EN ISO 19650-1) as a process input. The other input components are BIM and legal knowledge models (Dimyadi et al. 2017). ACABIM also supports supplementary human input by means of user-defined property sets or direct inputs through a user-interface.

The framework of ACABIM supports all input requirements necessary to conduct the experiment (see Figure 1). The building and equipment data is represented as an IFC model. The requirements specification, such as the material flows and operating material needs, is represented by a legal knowledge model (LKM) or requirements specification that can be maintained independently. The calculation process is represented by the BPMN workflow model (CAP), which queries data from BIM and ‘reads’ requirements in the LKM, as required. The calculation output is given through a user-interface as well as a printed report (Dimyadi et al. 2017).

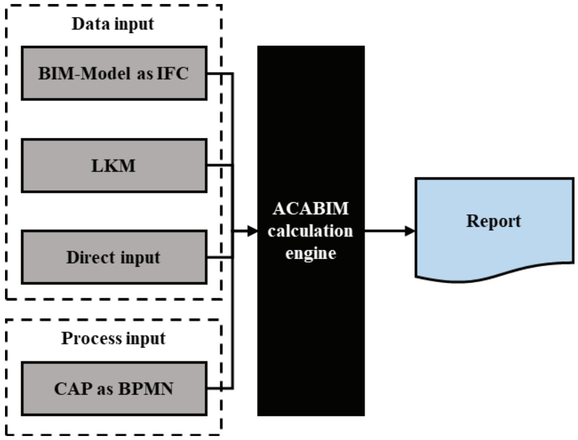

Figure 1: Framework of ACABIM (Dimyadi et al. 2017)

Experimental Settings

Our following use case is related to a real-world factory planning project in Bavaria, Germany, while the values are fictitious. In this scenario, a company's production area with two milling and four grinding machines were relocated to another building in the same geographical region. Two vacant factory buildings were found and fit for purpose. Firstly, the production machines as well as goods input and output were structured as an ideal layout by optimizing the material flow. Secondly, a real layout variant was generated for each contemplable factory building, by adapting the ideal layout to physical constraints imposed by the buildings, see Figure 2.

Factory Objectives and Evaluation Criteria

The layout variants in the use case are assessed considering the factory objectives of ecological sustainability, changeability, and economic efficiency. For these three objectives, four different evaluation criteria are derived. The ecological sustainability is measured by the space utilization rate (DIN 277) as well as the relative length of the operational material pipe network (Müller et al. 2013). Changeability was evaluated by the minimum floor load-bearing capacity (Heger 2007) and the economic efficiency by the material flow costs (Arnold und Furmans 2019), cf. Table 1.

Table 1: Overview on the factory objectives and the evaluation criteria

Factory objective	Evaluation criteria
Ecological sustainability	Space utilization rate
Ecological sustainability	Relative length of the operating material pipe network (pipe network length)
Changeability	Minimum floor load bearing capacity (load bearing)
Economic efficiency	Material flow costs

To calculate the evaluation criteria quantitatively, the following formulas are used: The **space utilization rate** is the ratio of the utilized spaces by production equipment and the available space:

$$\frac{\sum_{i=1}^{n} us_i}{as} = space\ utilization\ rate$$

with:

n: set of production equipment (= {1, 2, ..., n}),
us_i: utilized space of production equipment $i \in n$,
as: available space in the factory building.

A lower space utilization rate value indicates a better ecological sustainability.
The pipe network length is assessed by the weighted distance between the operational material source and the sinks, e.g., the production machines:

$$\sum_{i=1}^{n} d_{is} * q_i = pipe\ network\ length \quad (2)$$

(1)

with:

n: set of production equipment (= {1, 2, ..., n}),
d_{is}: distance between production equipment i and operating material source s (=d_{si}),
q_i: operating material need of production equipment $i \in n$,
s = 1.

The lower the pipe network length, the better is the ecological sustainability. In the presented use case, only one operating material source is given.
The **load bearing** is the minimal load-bearing capacity (lbc) in the available space:

$$\min lbc_i = load\ bearing, \forall i \in \{1, 2, \ldots, m\} \quad (3)$$

with:

m: set of load bearing capacities in the available space in the factory building (= {1, 2, ..., m}),
lbc_i: load bearing capacity of space $i \in n$.

A higher load bearing indicates a better changeability.
And finally, the **material flow costs** are calculated by the distances between the production machines, the goods input and output, multiplied by the material flow volume and a cost factor:

$$\sum_{i=1}^{n}\sum_{j=1}^{n} d_{ij} * v_{ij} * c = material\ flow\ costs \quad (4)$$

with:

n: set of production equipment (= {1, 2, ..., n}),
d_{ij}: distance between production equipment i and j (=d_{ji}),

v_{ij}: flow volume between production equipment i and j in a certain time period,
c: material flow costs per unit distance and per unit flow volume.

The considered planning horizon in the use case is one year. All distances are calculated as direct distances between the object centers.

Data Input

The factory buildings were originally generated using point clouds and modelled in *Autodesk's Revit*. The production machines, the goods input and output, and the operating materials source were incorporated into the model as conceptual bounding boxes and represented as *IfcSlab* entities, as there is no actual production equipment entity available in the latest IFC schema (Neuhäuser et al. 2021b). ACABIM was able to extract the bounding box geometry of the equipment for calculating distances between equipment and areas occupied by them within the space (Figure 2), which is represented by the *IfcSpace* entity. The space was supported by different foundation slabs represented as *IfcSlab* entities with a user-defined *BearingLoad* property set.

The matrix of operating material needs of the production equipment and the material flow volumes, viz. Table 2, which was sourced from simulation results of a production program, were represented as a set of IF-THEN rules in the LKM (Figure 4). The LKM was generated automatically using a spreadsheet.

For planning horizon, material flow cost factor and time-dependent calculations were also specified. The material flow cost factor for the real layout in factory building 1 is 12 €/ flow unit/ unit distance, which is the same amount as for the ideal layout. Due to a more complex transport around the grinding machines, the cost factor in building 2 is 15 €/ flow unit/ unit distance. The material flow costs are the only time-dependent evaluation criteria. As Table 2 shows, the input data is given per month, whereas the planning horizon is one year. Thus, the annual material flow costs should be multiplied by a factor of 12. The material flow cost factors were represented as attribute of each entity, which can be queried by CAP as BPMN.

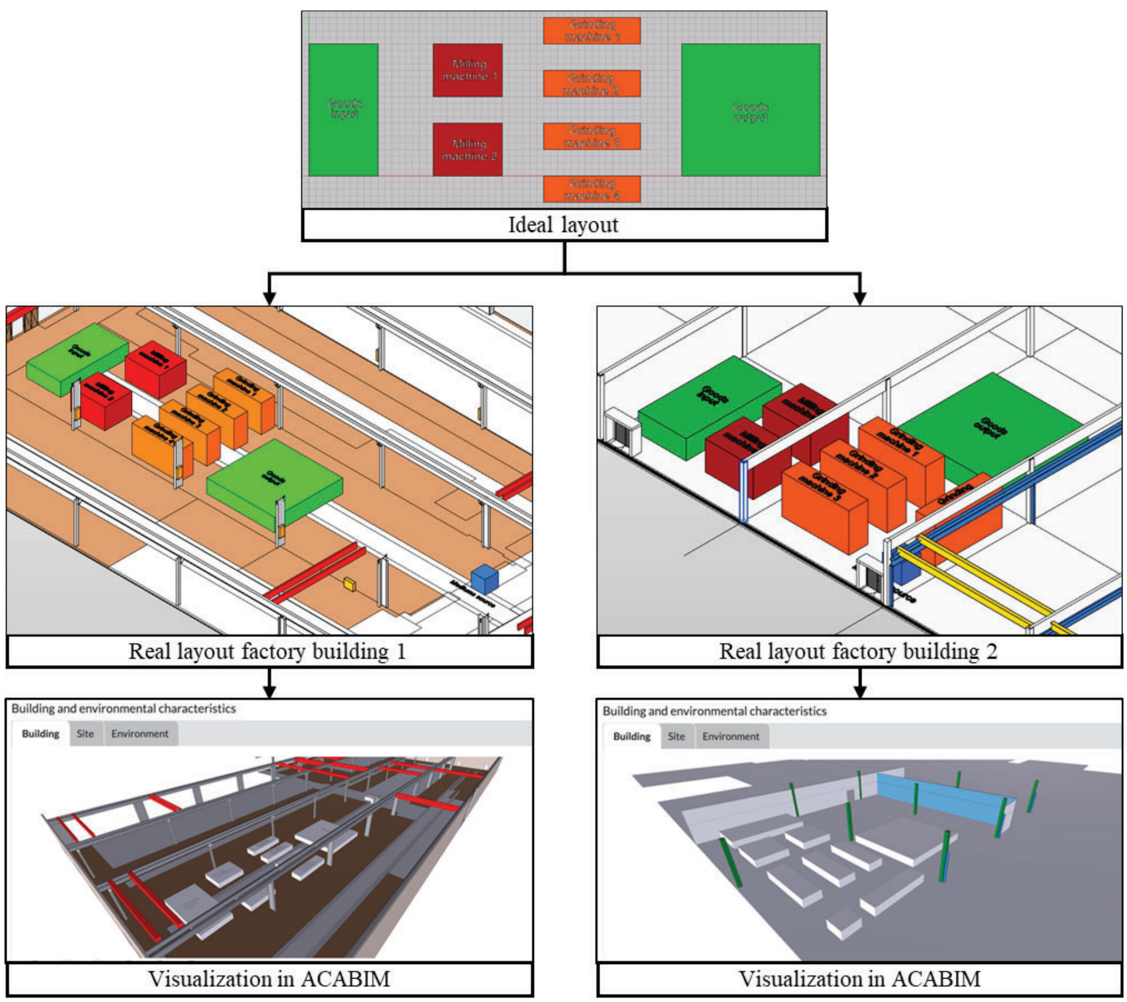

Figure 2: Ideal layout, real layout factory building 1, real layout factory building 2, and their visualization in ACABIM

Table 2: Material flow matrix between production equipment [flow units per month] with GI = Goods input, MM = Milling machine, GM = Grinding machine, and GO = Goods output

		To							
	Production equipment	GI	MM 1	MM 2	GM 1	GM 2	GM 3	GM 4	GO
From	GI	-	14	17	-	-	-	-	-
	MM 1	-	-	-	7	7	-	-	-
	MM 2	-	-	-	-	-	7	10	-
	GM 1	-	-	-	-	-	-	-	7
	GM 2	-	-	-	-	-	-	-	7
	GM 3	-	-	-	-	-	-	-	7
	GM 4	-	-	-	-	-	-	-	10
	GO	-	-	-	-	-	-	-	-

Table 3: Operating material needs of the grinding machines [totally needed units] with GM = Grinding machine

	GM 1	GM 2	GM 3	GM 4
Number needed	2	3	2	2

Table 3: Operating material needs of the grinding machines [totally needed units] with GM = Grinding machine

As shows, only the grinding machines require operating materials.

Since complexity increases quickly, even for these relatively simple calculations, the values and their influence on the evaluation criteria are summarized in Figure 5.

Process Input

Four CAP as BPMN were developed for specific data query and calculations in the experiment. A common CAP was also developed to perform the following basic procedures: 1) iterate each *BuildingStorey* and identify the production spaces by name, 2) Find each equipment within the production space and get its bounding box geometry and centroid, 3) Calculate distances between equipment from one centroid to another (Figure 4).

For space utilization rate, the CAP would only need to query the model data to perform the required calculations. For pipe network length and material flow costs (MFC), however, the CAP would also need to query the LKM model to get the required flow volume and operating material needs (Figure 6).

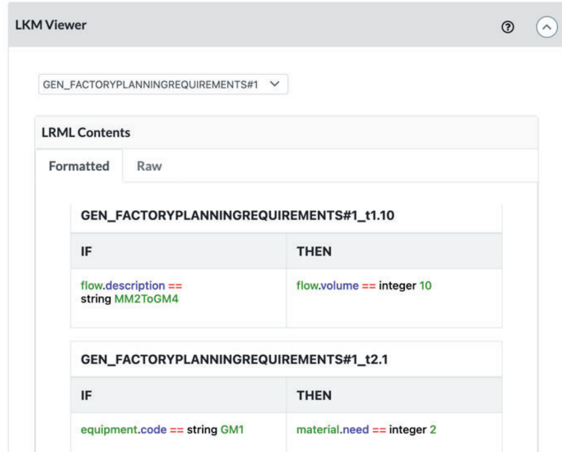

Figure 4: Requirements specification represented in LKM

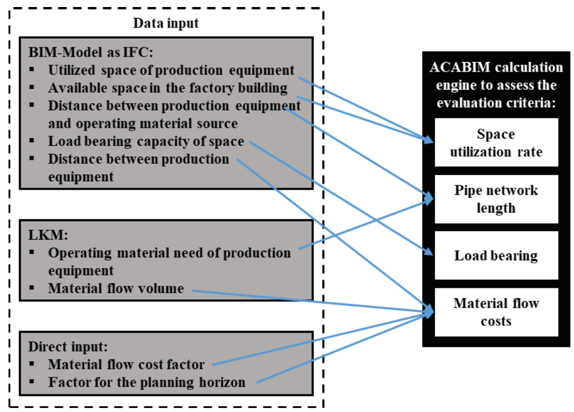

Figure 5: Connections between the data input values and the evaluation criteria

Discussion and Result Analysis

Table 4 shows the calculation results, which are outputted by ACABIM. The material flow costs are calculated for the ideal layout and to have a comparable value. The results show that the real layout factory building 1 is superior regarding the space utilization rate and the material flow costs, whereas the real layout factory building 2 is superior considering the pipe network length and the load bearing.

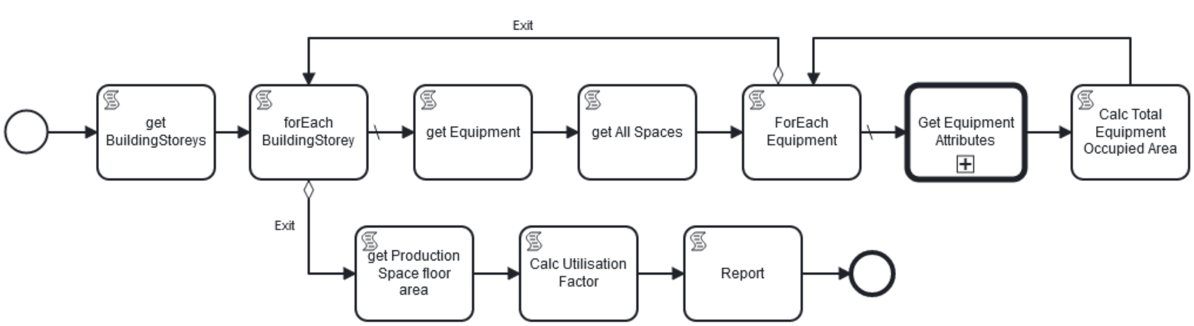

Figure 3: CAP as BPMN for calculating space utilization rate

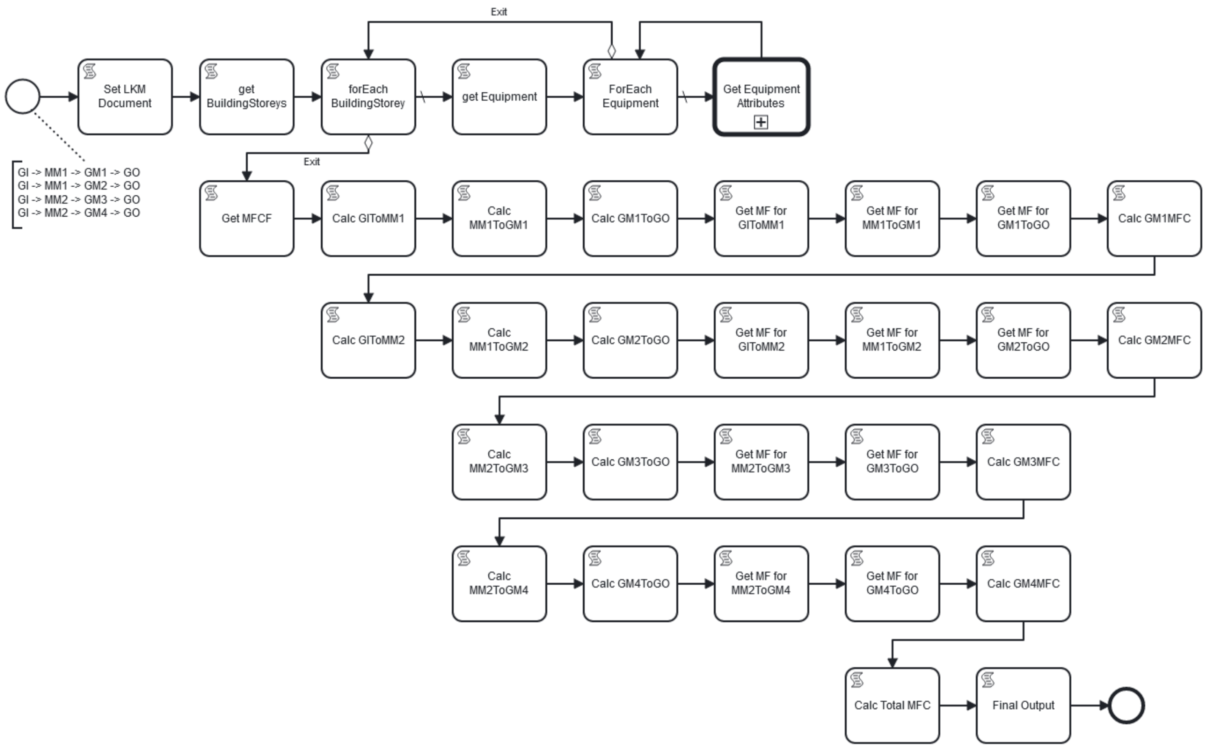

Figure 6: CAP as BPMN for calculating material flow costs

With regard to the research question, these results can be considered for a reliable decision for one of the factory layouts. Moreover, the experiment indicates that using ACABIM to systematically merge the data of BIM models and simulation results can automate the assessment of factory layout variants.

Table 4: Experiment result

Evaluation criteria	Ideal layout	Real layout factory building 1	Real layout factory building 2
Space utilization rate	-	**36.97 %**	27.89 %
Pipe network length	-	357.47 m	**77.22 m**
Load bearing	-	100 kN/ m^2	**150 kN/ m^2**
Material flow costs	10,304.44 €/ m	**12,479.93 €/ m**	15,094.57 €/ m

Developing CAP for the experiment is not trivial, but its visualization as a BPMN process diagram approach makes it practical. CAP employs a domain-specific query language called CAPQL that also incorporates standard JavaScript functions as well as custom functions. Although it requires a considerable effort to develop the initial CAP, once developed, they can be reused and easily adapted for different projects and scenarios. Another benefit of using open-standard workflow model is that they can easily be checked and verified for correctness before execution in editing tools available in the public domain.

In contrast to tools like visTABLE, which can only analyze the space utilization rate and material flow costs, the presented approach can calculate all mathematically expressible evaluation criteria. The results from layout planning in visTABLE can be extended by further quantitative evaluation criteria with the presented approach. Compared to a standard manual qualitative cost-benefit-analysis of the layout variants the presented approach is more elaborate. However, the presented quantitative approach seems to be more reliable and reproducible, if the data quality is sufficient.

Although, there is no standard representation of production equipment in the current IFC schema, a standard 'slab' entity could be used to exchange the required geometry quite well in the interim. Additional properties can be provided through user-defined property sets, if required.

Conclusions and Outlook

The paper presented an approach to systemically integrate BIM data and simulation results in a digital collaboration environment using the software tool ACABIM. Four different calculation processes for two layout variants were carried out. Thereby, four evaluation criteria were automatically assessed considering three different factory objectives: Ecological sustainability, changeability, and cost efficiency.

The current IFC schema does not support exchanging production equipment as standard entities that can be processed by tools such as ACABIM. However, as shown in the experiment, they could be represented reasonably well as an *IfcSlab* entity. Future developments of the IFC schema should focus on an extension regarding production entities. These developments would further establish BIM in factory planning and thus contribute to improving collaboration, planning and data quality.

With regard to the research question ACABIM seems to be an appropriate tool for automating the evaluation of factory layout variants. Compared to standard qualitative methods, decisions can be made more reliably and objectively if the data basis is sufficient. It leads to more trustworthy and transparent decisions in planning processes. As the manual development of CAP as BPMN is relatively complex, this approach is recommended for highly complex layout variants or if the calculations can be reused in different projects and setups. Interesting further research fields would be an automatic generation of CAP based on a set of criteria as well as the automation of calculation runs by CAP. The approach could also be extended to provide automatic layouts or for optimising equipment layout. Thus, in the context of an optimization problem, the evaluation results would be part of a control loop for new layout variants.

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