A literature review on the cross-domain usage of digital factory twins within design time

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Abstract. In a globalized production environment companies are confronted with shortening product life cycles leading to shortening factory system life cycles. To overcome this issue, factories have to be (re-)built faster. The design time is a crucial phase in which many different disciplines of different domains have to work together in a major planning project. Currently, various experts in the respective domains of e.g. production system planning, automation and building are commonly working on their silo models resulting in different and sometimes contradictory information depending on the perspective of planning. While model-orientated, collaborative planning approaches like Building Information Modeling (BIM) have become familiar with the domain of factory planning, there is still a lack of combining the different factory data models holistically to connect all elements of production regarding information of products, processes and resources. Besides the BIM methodology several other forms of virtual factory descriptions, like the digital factory twin have emerged.
In this work, a systematic literature review is conducted to present the current perspective on creating factory data models about a cross-domain usage and modeling approach. In analyzing the current use case definition of factory models the opportunity is seen to point out the importance of the combination of holistically linked factory data models with a multipurpose design. In doing so, a possibility is seen to overcome the mentioned obstacles of planning while raising the value of the created models. This demonstrates the need for a concept of modeling a digital factory twin, created for cross-domain usage.

Keywords: Holistic Factory Model · Factory Planning · Building Information Modeling · Digital Twin · Collaborative Planning

1 Introduction

A factory is a central location for the value creation of companies [44]. In times of shortening product life cycles (PLC) also factory life cycles (FLC) are shortening as production systems have to adapt to changing requirements of the production factors [15]. Besides the dynamization of PLCs other change drivers like globalization, technological advancements and the development of new markets force factory systems to adapt to new requirements quickly [23]. For this reason, factories need to be planned and built or adapted faster. In contrast, factory planning projects are often facing delays as well as increased costs [40].

Planners complain about poor communication and coordination in planning projects between the involved disciplines, unclear responsibilities and low transparency in the planning process [34]. To answer that, model-based, collaborative planning approaches like the BIM Methodology were adapted from the building industry [33].

To overcome the issues stated above, there is a need to speed up the factory planning process and reduce the challenges involved planners are facing. The most suitable is seen in a holistic planning approach based on model-based information exchange between all stakeholders involved in a factory planning project since information logistics is assumed to be the key enabler [34]. For that a deeper understanding of the planning process, currently used factory data models (FDM) and the usage of the information in the FLC about a digital factory twin is necessary. In this work, different factory modeling approaches and their application in the planning phase in combination with the underlying coordination process are examined. For those different perspectives on the planning process, the literature is analyzed by conducting a systematic literature review. The primary research efforts concern the current state of model-based information exchange in factory planning projects with regard to a multipurpose cross-domain use case approach. It is seen as a key enabler for efficient modeling and thus an efficient factory planning process. A better understanding of the different perspectives of planning disciplines in combination with the already existing solutions (e.g. model-orientated planning processes between the domain of building and production [42]) is seen as a foundation for the development of a holistically networked factory model with corresponding collaborative planning process as a next step in the research field of factory planning.

This work is structured in the following way. In section 2 the theoretical background is presented. After that, the methodological approach is outlined. In section 4 the findings of the conducted review are presented and discussed. Finally, the outlook is presented as well as a proposal for future research.

2 Theoretical Background

Factory planning is defined as a "systematic, objective-oriented process for planning a factory, structured into a sequence of phases, each of which is dependent on the preceding phase, and makes use of particular methods and tools" [50] and is considered a separate field of research [53,44]. As mentioned in this definition, it takes place in a part of the FLC and is structured in phases and is a highly collaborative process that needs information exchange between the involved disciplines. The following sections describe these perspectives of the factory planning process and the obstacles with the associated fields of research.

2.1 Factory planning process and phases of factory life cycle

A dominating factory planning process description is given by the *VDI 5200*. It structures the planning project into seven phases and follows a process-orientated, sequential approach with the possibility of iterative processing [50]. In contrast to that, a modular approach based on respective planning content is presented by the research of the *WZL (RWTH Aachen)*. A map has been created in which the different modules (sub-planning tasks) are connected. It shows the interdependence between the modules, how they affect each other and which input and output are needed for processing [7,35,28]. As shown, there are competing process descriptions for factory planning, leading to uncertainty in the structuring of projects. The work packages respective phases have a logical order that is related to the FLC. These phase models are described in the following section.

The life cycle of a factory can be divided into three major phases: design, construction and operation. The starting point for going through this FLC is event- or problem-oriented and after completing a cycle another cycle could start, or the factory could be put out of operation [37]. Since a factory is also a building, it can also be implemented into the building life cycle, which structures the phases in more detail [3,25]. The concept of the digital factory is settled also along the whole FLC. It refers to the planning aspect, which was later published within the *VDI 4499* but also contains the phases of operation [49]. It aims for the holistic planning and continuous improvement of the structures, processes and resources in the connection of the factory and the product [4].

Compared to construction and operation the phase of planning is structured in a far more precise way. The definition of the phases from the construction domain depends on the respective countries [41,46]. Depending on the discipline, planners orientate themselves in Germany on the *Fee schedule for architects and engineers (HOAI)*, which separates the planning phase into nine so-called "service phases" [24]. In contrast to that, planners of the domain production refer to the *VDI 5200* which also connects the phases of factory planning and the service phases of *HOAI* [50].

Another concept used to describe the factory is the digital twin [38]. As a digital representation of the factory, the concept of a digital twin has different life cycle phases. Also, depending on the definition, there is a differentiation between the digital twin prototype in the design phase and the digital twin instance in operation [21]. This difference was made mainly because of the functionality but it has also a time aspect. In comparison to that, the terms digital twin in design time and runtime make a clearer reference to the life cycle phases [5]. As shown, multiple definitions of FLC phases are existing regarding the domain and concept used (e.g. digital twin, digital factory). This makes structuring a project and coordinating the information flow hard, as there is a need for translation between the different structuring approaches.

2.2 Data models for factory planning and information exchange

Models within the factory planning process have a purpose, are based on the processes in which they are used and are used in collaboration with the respective disciplines [49]. In terms of a BIM-orientated approach, BIM use cases are derived from the aims considering the factory, the project and the BIM approach itself [30]. Also, digital twins are set up to serve specific use cases [6]. The definition of these underlying use cases is more or less standardized depending on the approach leading to the use of different models.

In terms of digital data models, different types have become popular. As a container of different types of models, the Automation Markup Language (AML) has been developed as an information exchange solution between engineering tools mainly for disciplines concerning automation issues [16]. It is also discussed how AML can be a part of the interoperable framework for the creation of a digital twin in the form of an Asset Administration Shell (AAS) [17]. In addition to the expression digital twin, terms like digital shadow as a step to the evolution of a digital twin were used [1]. These structures are unclear as it has multiple definitions, also depending on the field of research [5,18].

An approach for integrated factory planning in combination with the domains of production system planning and building is found in the BIM Methodology [10]. A BIM-Model contains information on the building as well as information on the used equipment [43] which can be used for factory layout planning [33] as well as semantic collision detection within the BIM-Model [19]. One advantage is the use of open formats (Industry Foundation Classes - IFC) to secure interoperability between planning software used by the different planning disciplines [32]. As a static representation of the building with its operation resources a BIM model contains just a limited part of the information needed in a factory planning project [43]. Additionally, different data models were created for defined purposes, like variant comparisons within the planning progress [45].

A broad amount of different models for different applications have been developed over time. Only some focus on the collaborative planning approach like AML or BIM Models. In this work, a FDM can be seen as a digital twin in its design time, as there is no unified definition of a digital twin. A holistically networked FDM expresses a model at a higher level, combining different sub-models (e.g. BIM-Models and AML-Models).

The exchange of information is fundamental as a factory planning project is done by several disciplines that are mutually dependent on each other's information. Data and information exchange in factory planning projects can be considered on different levels, with regard to the form and contents of information sharing [53]. The information and data exchange can be arranged via proprietary (1) or neutral and not standardized (2) or neutral-standardized data formats (3) [4]. The BIM Methodology in particular makes it clear that there is an enormous need for information exchange in the planning phase, as the disciplines involved are dependent on information from the other participants in the iterative planning process [32,7]. Especially while conducting the BIM-Methodology the process of information delivery is well described and becomes more and more standardized [33,32]. Not only the exchange itself but also the coordination of the different planning disciplines regarding their individual information flow is considered [20].

As pointed out, a huge variety of approaches regarding factory models and their modeling within the factory planning process exist. However, the current literature shows unrealized potential in terms of efficient, holistic and cross-domain factory modeling. In the course of this, this review critically analyzes the following research questions (RQ):

RQ-1: *What levels of modeling are used in the model creation process regarding the planning phase?* The first research question aims to give an insight, into how detailed the planning process is structured in the respective source. A structured and detailed implementation into the planning process is one fundamental of a coordinated planning approach.

RQ-2: *How can factory models from the literature be classified in terms of multiple utilities?* This RQ gives an insight into whether the modeling process is just meant to fulfill one use case or if it's created to serve several use cases which raises its value for the factory life cycle.

RQ-3: *To what degree is information exchange between the involved disciplines in the model creation process defined?* To answer this RQ, the literature is analyzed to find out if the modeling process within the design time of the factory is described regarding the information exchange between the collaborating disciplines within the project. As the defined coordination process for the information exchange is considered to be crucial for efficient modeling, a detailed description should be described by the authors in the literature.

3 Methodology

Based on the given background in Section 2 an exploratory research approach is chosen to investigate the current status of the usage of FDMs and the underlying information exchange between the involved disciplines in the factory planning process critically. To give an overview of this field, a literature review is used in a structured, three-stage approach of data acquisition, data filtering and data analysis [47]. In Table 1, the steps of data acquisition and filtering are described. The generic search string has been modified in an iterative approach by using keywords based on the results of Section 2. Finally, the generic search string was adjusted to:

TITLE-ABS-KEY(("Data Model" OR "Information Model" OR "Digital Twin" OR "Digital Thread" OR "Asset Administration Shell" OR "Digital Factory" OR "Building Information Model" OR "Digital Storage" OR "AAS" OR "BIM") AND ("Factory") AND ("Planning" OR "Operation" OR "Modeling") AND ("Exchange" OR "Collaboration" OR "Flow" OR "Interchange" OR "Management"))

To filter the acquired data, only the fields of Engineering and Computer Science were considered. This review has been limited to peer-reviewed articles. In total 1074 publications have been found of which 214 remained after using the inclusion criteria. After this procedure, a forward and backward literature search was conducted. The process for the finally remaining 21 titles within the stage of data filtering can be found in Figure 1.

The categorization of the titles within the stage of data analysis is done in a step-wise approach. After a first exploratory examination of the relevant categories regarding RQ-1 to RQ-3, a systematic assignment of the titles has been done. This approach was chosen, as to the best of the author's knowledge, within this field of research no previous analysis regarding this dimension has been done.

Table 1. Summarized research protocol of the conducted literature review with the inclusion criteria used

Criteria of the literature review	Criteria value
Databases	Scopus, Dimensions, Web of Science
Language	English
Publication year	2018 - 2024
Fields of research	Engineering, Computer Science
Publication Type	Article
Data downloaded	03/04/2024

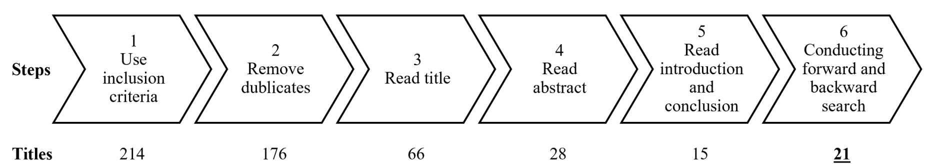

Fig. 1. Research steps of the conducted literature review with the remaining titles

4 Findings and Discussion

An overview of the bibliometric analysis of the review is shown in Figure 2. The body of literature is displayed in Table 4 in the appendix. With 21 titles published in the last five years, this specific field of research seems to be in an initial state. Due to the results, nine different engineering disciplines are working in this field of research. Industrial Engineering (29%) is the most represented. Based on the different disciplines working on this topic, the scope and the perspective differ within the literature. In addition to that, a broad range of concepts are used of which a digital twin was the most frequently mentioned one with 43 %, followed by virtual factory (19 %) and BIM models (14 %).

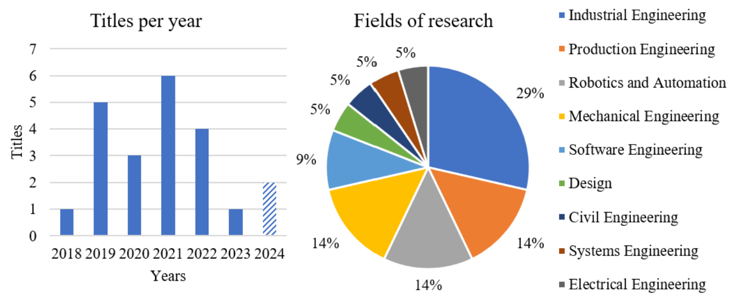

Fig. 2. Results of the bibliometric literature review with regard to the development over time and the fields of research involved

4.1 RQ-1: What levels of modeling are used in the model creation process regarding the planning phase?

To measure the characteristic within this dimension, the literature can be categorized into **rough** (not more detailed than "planning phase"), **detailed** (a more detailed structure than just "planning phase") and **section** (just one part of the planning phase). The analyzed titles show that nearly half understand the planning phase as a monolithic phase in the creation process of the factory model within the FLC. Five out of eight titles within the category "detailed" show non-standardized phases and respective process steps, presented in Table 2.

Table 2. Challenging transferability between non-standardized phase models due to different definitions of planning phases

No.	Sub-phases of the planning process within the modeling	Source
1	product design, process design, plant design	[27]
2	conceptual, detail, design, as-built	[29]
3	planning decision, design, construction	[54]
4	production requirements, design, engineering, integration and ramp-up	[55,56]

Three titles are settled in just a sub-phase of the planning phase and 38 % consider the modeling process in a more detailed implementation regarding the planning phases. In the category "detailed", three different subcategories have been identified of which two show an implementation into standardized phase models (building life cycle [3] and VDI 5200 [50] in combination with the HOAI [24]) of the factory planning process. The complete results can be found in Figure 3.

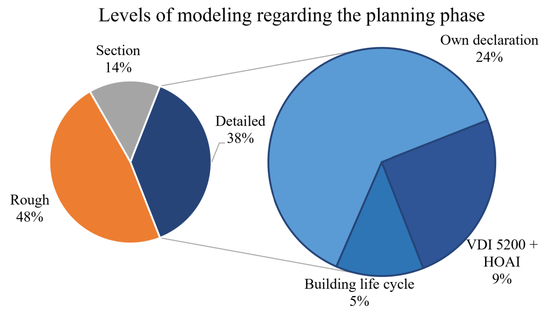

Fig. 3. Results of RQ-1: Differences in the level of detail used to describe the modeling within the design time

Based on the lower level of detail considering the subdivision of the planning phases of titles out of the category "rough", a more detailed structuring of the information flow within a project is harder to implement in contrast to the more detailed and standardized phase models. Titles focusing on the BIM approach seem to have a bigger connection to the phase models of planning [1,9,10]. In contrast to that, authors using the expression digital twin tend to see the planning phase in a monolithic way. In addition to that, the sub-phases defined without reference to standardized phase models (see Table 2) are various and hard to synchronize with the standard phase models. Regarding this, for practitioners the transfer of work processes considering the information transfer and modeling is difficult between different projects.

To sum up, the current literature considers the integration of factory modeling into the formal phase-orientated planning process of a factory in a minor way. Just three out of the 21 analyzed titles implement the modeling into standardized and detailed planning phases. However, for the collaborative modeling of factory models in terms of use cases for different stakeholders, a detailed subdivision is considered beneficial as it is seen as a foundation for a more precise structuring of the information flow. This is expected to be supportive of the coordination of the disciplines involved.

4.2 RQ-2: How can factory models from the literature be classified in terms of multiple utilities?

The literature can be categorized into **not described** (the authors don't mention possible use cases), **shown in general** (multiple use cases are named in a general manner), **shown in detail** (multiple use cases are described in a detailed manner) and **specific case studies** (specific use cases are described in form of a case study). Considering RQ-2, the analysis presented in Figure 4 shows, that one-third isn't describing multiple use cases as a reason for modeling a holistic factory model. On the other side, two-thirds of the analyzed titles consider multiple use cases in modeling. 14 % do it detailed in presenting a case study.

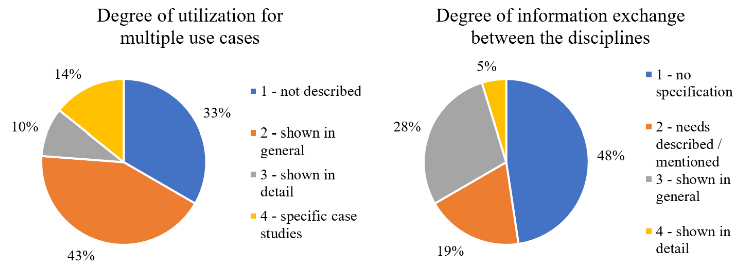

Fig. 4. Degrees of utilization for multiple use cases and information exchange between the involved disciplines of the created factory models

Creating a factory model is done to fulfill specified goals respectively use cases. In serving multiple use cases, the value of a holistic factory model rises. As the literature shows, the majority of authors think about the use of one virtual factory representation for several use cases. However, only the minority is doing it in a detailed way while presenting case studies. Though, we did not analyze how strongly the use cases served by one model differ considering possible usage of different disciplines because the degree of use case definition described in the analyzed literature does not allow such an examination. This shows that the modeling in terms of multiple utilization is just beginning to develop. It should be clarified, what the reason for the low level of detail in terms of multiple utilization is.

4.3 RQ-3: To what degree is information exchange between the involved disciplines in the model creation process defined?

This RQ can be categorized into **no specification** (the coordination process of information exchanged isn't mentioned at all), **needs described/mentioned** (The need for a coordination process is described or the coordination process is mentioned), **shown in general** (the coordination process is described roughly and generically) and **shown in detail** (the coordination process is described detailed regarding the disciplines and the needed information) In contrast to the degree of multiple utilization (Section 4.2), the information exchange between the disciplines involved is not mentioned by 48 % of all titles (see Figure 4). Just about one-third are discussing it, of which only one is doing it in detail. This leads to the assumption, that the authors primarily focus on the virtual representation respective to the model and its architecture compared to modeling. Modeling is used to describe the process of creating the virtual factory model regarding the collaborative interaction between the involved disciplines. In combination with the findings of RQ-2 and RQ-3, a two-dimensional view regarding the information exchange within the modeling of a holistic virtual factory model is possible (see Table 3). The optimal situation is considered if a title would be categorized in both dimensions in the highest score (lower right half of the cross table).

However, no title is considered to be fulfilling these requirements. The majority of titles can be found in the upper left of the table. No matter, what the underlying structure is called (e.g. virtual factory, digital twin), there is a lack of structure regarding the coordinated information exchange within the phase of planning.

In combining research in the fields of model and modeling in an equal weighting, a benefit in the practical implementation not just in one project but in the whole way of planning factories is seen. While the holistic factory model serves not only for several use cases but also for several disciplines, the value of the approach is expected to rise. This indicates strengthening the research in the model-based information exchange between the involved disciplines in a coordinated way. This intensifies when the used sub-models of the holistically linked FDM are overlapping in their information content, for example, BIM-based layout in combination with production process simulation studies and system models for automation planning. In addition to that, the implementation of standardized phase models of factory planning is seen to be beneficial as it lowers the entry threshold for use in the industry. Efforts should be put into using partial solutions, like the research in the field of BIM-based factory planning regarding the concept of Level of Coordination [31], and adapt them to the holistically linked factory model.

Table 3. Combined analysis of **RQ-2** and **RQ-3** regarding the degree of utilization for multiple use and information exchange within the body of literature

	Cat. RQ-3			
Cat. RQ-2	not described	shown in general	shown in detail	specific case studies
no specification	7	1	1	1
needs described	0	3	0	1
shown in general	0	4	1	1
shown in detail	0	1	0	0

5 Outlook

In this work, a critical review of the current status of the development of holistically networked FDMs in the planning phase was conducted. Therefore, literature regarding the modeling and information flow between the involved disciplines in combination with the level of detail in terms of the underlying phase model of planning was analyzed. A systematic literature review was therefore carried out to critically examine the current literature in this field of research. The analyzed titles were structured according to the given RQs. However, the size of the body of literature is a limitation. Including the publication type of conference papers could broaden the view of the latest research efforts. The results show, that there is a lack of coordination in collaboration between the stakeholders involved, especially if the authors a directly using the term digital

twin for the created model. Most titles show no focus on modeling for cross-domain use of FDMs. One symptom of this could be the low level of detail in relation to the described planning phases of a factory.
Future research should focus on the modeling aspect in terms of integrating the sub-models of the involved disciplines. For that, a more detailed analysis of what kinds of FDMs are currently used in the factory planning process regarding the associated modeling method combined with current challenges is planned. Through implementing a planning and coordination process in consideration of standardized planning phases and best practices of the sub-methodologies like the BIM approach, pragmatic solution modules are seen for the implementation of digital factory twins in the design time. In consideration of the use case orientation, a framework should be developed which describes the model structure of a digital factory twin using the approach of linking sub-models (e.g. BIM, AML, AAS) using open formats and standards. This holistically linked FDM should serve for multiple cross-domain use cases while describing the factory holistically in terms of the field of served use cases. As already mentioned, the described model and the process of modeling must be carried out with the same research effort, taking into account the different disciplines and using detailed and standardized phase models within the FLC.

6 Appendix

Table 4. Body of literature of the conducted literature review

No.	Source	Result RQ-1	Result RQ-2	Result RQ-3
1	[1]	detailed	shown in general	needs described / mentioned
2	[2]	rough	not described	no specification
3	[8]	detailed	specific case studies	shown in general
4	[10]	rough	specific case studies	no specification
5	[9]	detailed	specific case studies	needs described / mentioned
6	[11]	rough	not described	no specification
7	[12]	section	not described	no specification
8	[13]	rough	shown in general	needs described / mentioned
9	[14]	rough	not described	no specification
10	[22]	rough	shown in general	shown in general
11	[26]	section	shown in detail	shown in general
12	[27]	detailed	shown in general	needs described / mentioned
13	[29]	detailed	shown in general	shown in general
14	[36]	rough	not described	no specification
15	[39]	rough	shown in general	no specification
16	[48]	section	not described	no specification
17	[51]	rough	shown in general	shown in general
18	[52]	rough	not described	no specification
19	[54]	detailed	shown in general	shown in detail
20	[55]	detailed	shown in detail	no specification
21	[56]	detailed	shown in general	shown in general

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