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Fabian Bermpohl

fabian.bermpohl@igcv.fraunhofer.de

Fraunhofer Institute for Casting Composite and Processing Technology IGCV: Fraunhofer-Institut fur Giesserei- Composite- und Verarbeitungstechnik IGCV https://orcid.org/0000-0001-8585-0642

Christian Johannes Eckart

Fraunhofer Institute for Casting Composite and Processing Technology IGCV: Fraunhofer-Institut fur Giesserei- Composite- und Verarbeitungstechnik IGCV

Sven Forte

Contact Software

Anja Munzke

Fraunhofer Institute for Casting Composite and Processing Technology IGCV: Fraunhofer-Institut fur Giesserei- Composite- und Verarbeitungstechnik IGCV

Rüdiger Daub

Fraunhofer Institute for Casting Composite and Processing Technology IGCV: Fraunhofer-Institut fur Giesserei- Composite- und Verarbeitungstechnik IGCV

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METHOD FOR DIGITAL INFORMATION CONTINUITY IN THE CONTEXT OF SHORT-CYCLED FACTORY REPLANNING

Fabian Bermpohl[1*] (0000-0001-8585-0642), Christian J. Eckart[1] (0009-0003-4122-2806), Sven Forte[2] (0000-0002-3754-6475), Anja Munzke[1] (0009-0006-7843-1996), Rüdiger Daub[1,3] (0000-0002-5120-4228)

[1] Fraunhofer Institute for Casting, Composite and Processing Technology IGCV, Am Technologiezentrum 10, 86159 Augsburg, Germany

[2] CONTACT Software GmbH, Wiener Str. 1-3, 28359 Bremen, Germany

[3] Institute for Machine Tools and Industrial Management iwb at the Technical University of Munich, Boltzmannstraße 15, 85748 Garching bei München, Germany

*Corresponding Author

Fabian Bermpohl, M.Sc.

+49 (0) 821 90678-145

fabian.bermpohl@igcv.fraunhofer.de

Abstract

Factory operators face a challenging business environment, necessitating more frequent factory upgrades. State-of-the-art approaches for factory planning include extensive data preparation efforts, accounting for approximately 60% of the total planning effort. Within the last few years, model-based approaches such as building information modelling have significantly improved factory planning efficiency. However, the holistic digital factory models that stand at the end of the factory planning phase are not effectively transferred into the operational phase. They are, therefore, not linked to the digital twin and are not updated during the operation phase. Consequently, these digital factory models become outdated and cannot be used for subsequent factory replanning. Based on a structured literature review and two focus group discussions, this paper proposes a new method for transferring holistic digital factory models into the operations phase and to provide an updated digital factory model at the interface to the next replanning phase. The feasibility of this method is validated at the application scenario of a laboratory for additive multi-material manufacturing with data from energy monitoring and MES.

Keywords

BIM, Digital Twin, Factory Design, Life Cycle, Digitization

1 Introduction

During factory operations, three central triggers necessitate technical changes within a factory. These triggers are the introduction of new products, the implementation of new technologies, or changes in the production program [1]. They occur more frequently in a dynamic business environment characterized by global competition and increasingly stringent government regulations. Consequently, the need to adapt existing factories and the associated factory replanning processes will arise in shorter cycles. [2]

Alongside, the advancement of digitization has precipitated the emergence of digital models and technologies for factory planning and operation, thereby establishing a centralized data foundation to support the execution of tasks across each respective phase. In factory planning, a current trend involves the increased use of Building Information Modeling (BIM) [3]. BIM models are becoming essential as central data repositories for planning results throughout the entire planning process [4]. In factory operations, a key focus area is capturing condition data from physical factory assets and the subsequent processing of this data within a Digital Twin (DT) [5].

However, factory planning and factory operations are predominantly considered separate. This results in a lack of digital continuity between the information contained in BIM models used during planning and the DT utilized in operations, and vice versa [6]. Each adaptation cycle necessitates substantial effort in both the factory planning phase and the operational phase to collect and utilize data from the other phase. In the context of factory planning, this data preparation can account for up to 60% of the total effort involved in a project [7, 8]. Ensuring Digital Information Continuity (DIC) could reduce the need to prepare data at the start of the factory planning and operations phases. Examples of such data preparation include the collection of machine-related data, e.g., availability rates, energy consumption, or maintenance requirements. These are often estimated during the initial planning phase but must be replaced with actual operational data during replanning. Furthermore, errors resulting from manual information transfer could be eliminated. Therefore, a digitally integrated closed-loop approach is necessary to connect the information from factory planning with the information from factory operations.

This paper is based on the central thesis that the efficiency of short-cycled factory replanning can be enhanced by establishing a closed-loop system that realizes cross-life-cycle information continuity of planning and operational data.

Fig. 1 illustrates this objective vision of DIC in the context of short-cycled factory replanning. This objective vision first highlights that planning data is available upon

completion of the initial factory planning. This includes not only the BIM model but also additional planning data. In practice, the integration of all relevant planning data into a holistic digital factory model (HDFM) is often achieved through a Common Data Environment (CDE) [9, 10]. Furthermore, the objective vision illustrates that this planning data should be transferred into factory operations, where it is utilized in two main ways: first, as input for the DT, and second, to create the BIM model in its "as-built" or "as-operated" state. Moreover, operational data is produced during factory operations. When integrated with existing planning data, this data forms the basis for factory replanning. New BIM models and additional planning data are created during the factory replanning phase, as in the initial factory planning phase. These are once again integrated into holistic digital factory models and made available as "replanning data" for factory operations. The continuous transfer of replanning data into factory operations and the DT, and the equal transfer of operational data from the DT into factory replanning, ultimately establishes a closed-loop system. However, a general method describing the development and application of such a system has yet to be developed (see Chapter 3).

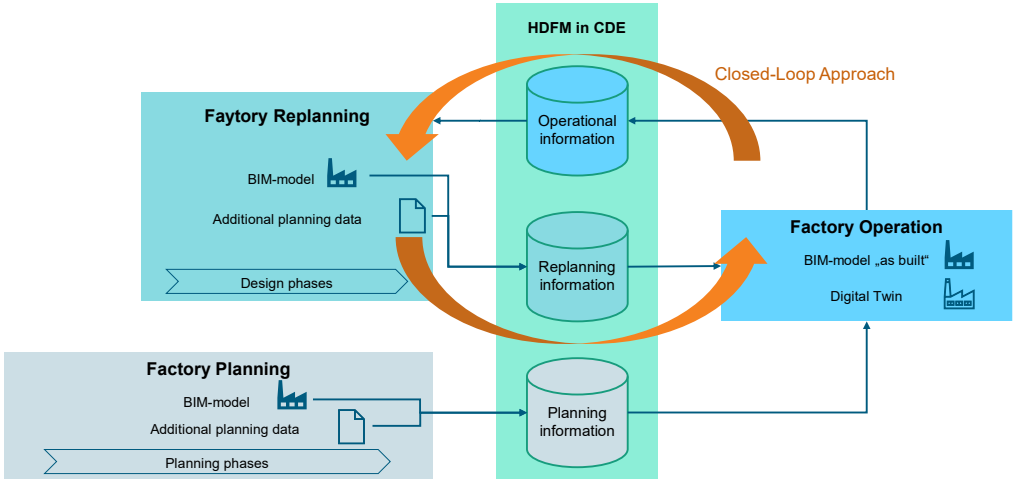


Fig. 1 Objective vision of cross-life-cycle digital information continuity in the context of short-cycled factory replanning

2 Fundamentals

To develop a method for realizing the objective vision, it is first necessary to define DIC and to examine the key underlying technologies: BIM, HDFM in a CDE, and DT.

2.1 Digital Information Continuity

In factory planning, DIC refers to the consistent usability of data and models across life-cycle phases [11]. Based on continuous engineering, information should be reusable throughout the value chain with minimal loss or effort, and without redundant work or

data entry [12]. This requires integrated engineering tools, consistent data management, standardized interfaces, and open exchange formats [13]. Accordingly, this paper defines DIC as the consistent, traceable transfer and reuse of data and models across factory planning, operation, and replanning, with minimal information loss, manual transformation, and redundancy. DIC does not necessarily imply that every transfer is fully automated. Therefore, the degree of DIC is subsequently differentiated into direct, indirect, and lost information transfer (see Chapter 7).

2.2 Building Information Modeling

The collaborative working methodology, BIM, originated from the domain of building planning. Within the last years, many authors have contributed to transferring BIM from building planning to the higher level of factory planning, and include the domain of production systems planning as an equally integral component [14–17]. The focus of BIM is on including planning data from all relevant stakeholders into shared digital models under the data standard Industry Foundation Classes (IFC) [15]. These models are further referenced to as Factory-BIM models.

The Level of Development (LOD) describes the level of detail and reliability of a model, which increases progressively throughout the planning phase until reaching its highest detail at the end of the realization [17]. The LOD is relevant because information used for operation and subsequent replanning must correspond to the factory after realization. Consequently, an as-built or as-operated Factory-BIM model is required as an input to replanning, rather than a model representing only an earlier planning state.

One main lever to achieving interdisciplinary collaboration is the integration of both geometric and alphanumeric data [14]. However, *Schäfer et al.* stated that mainly static master data is represented within Factory-BIM models [16]. Additional information relevant to factory replanning therefore cannot be included in Factory-BIM models.

2.3 Holistic Digital Factory Model in a Common Data Environment

In this context, HDFMs provide centralized storage of all relevant information generated throughout the factory planning phase [10]. This includes Factory-BIM models in the IFC format and additional planning information such as work plans, Bill of Materials, item master data, or factory planning goals and restrictions. These HDFMs can be realized through the combination of all this data within a CDE [9]. A CDE is a collaborative platform that provides a centralized and structured repository for managing, sharing, and accessing all relevant data across different stakeholders and phases [18].

2.4 Digital Twin

DTs are virtual representations of physical products, processes, or systems [19]. At the same time, various definitions of the DT exist, depending on the level of analysis (e.g., product, building, equipment) [20, 21]. The DT at the consideration level of the factory system is further referred to as Digital Factory Twin (DFT). It is important to note that the accuracy of a DT's representation of real assets depends on the specific use case [22]. In the context of the DT, the open data standard of the Asset Administration Shell (AAS) is frequently employed [23]. Additionally, DTs can be classified based on the degree of automation in their data flow between the physical and digital components. While there is no universally accepted definition, this article aligns with the understanding of *Bergs et al.*, who define a DT as existing when a unidirectional automated data flow of condition data from a physical asset to its digital counterpart is established, and new insights (information) are generated as a result [24].

3 State of the Art

In combination, the Factory-BIM model provides the structured planning model, the HDFM in the CDE integrates this model with additional planning information, and the DFT provides use-case-specific operational data and derived information. The research challenge lies not in these individual technologies but in their synthesis to realize cross-life-cycle DIC. Therefore, these fundamental technologies and the objective vision (Fig. 1) serve as the foundation for establishing specific target criteria that a method for DIC in the context of short-cycled factory replanning should fulfill:

- First, it is imperative to consider the planning and operational phases of the factory to ensure the aspect of cross-life-cycle information transfer.
- Second, it must account for the core technologies of the Factory-BIM model, its extension to HDFM within a CDE, and the DFT.
- Thirdly, in the context of software-independent DIC, it is imperative to employ open standards such as IFC and AAS. It is also necessary to define the precise information objects to be transferred digitally.

In this context, a structured literature review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework was conducted to identify relevant sources. The search key *(TITLE-ABS-KEY ("Building Information Modeling" OR "BIM") AND TITLE-ABS-KEY ("Digital Twin") AND TITLE-ABS-KEY ("Factory"))* is used in SCOPUS and Web-of-Science. It combines three fundamental aspects:

- The consideration of BIM as a central planning technology.
- The DT as a core operational technology.
- The inclusion of the term "factory" ensures that the factory level is addressed, rather than solely the building domain or individual assets at the shop-floor level.

The search conducted on the 6th of September 2026 yielded 91 results. Following the PRISMA framework [25], within the identification phase, 13 duplicates and five conference proceeding collections (no single papers) were removed. Subsequently, the title and abstract of the remaining 73 papers were screened. Based on this screening, 39 papers were excluded. The remaining 34 papers were sought for retrieval. However, two papers were not retrieved:

- *Choi & Song* [26], because it was only available in Korean
- *Rihs et al.* [27], because it was not available as a full-text in the databases accessible to the authors. However, based on the title and abstract, this source is strongly focusing on the building domain and a one-off as-built documentation of brownfield sites.

The remaining 32 sources were retrieved as full papers and assessed for eligibility:

- 14 papers do not address the (re-)planning phase and its central technology BIM [28–41].
- Six papers do not address the DT as a core technology within the operations phase [35, 42–46].
- Eight papers do not address the factory level / domain [30, 33, 35, 36, 40, 47–49].

Some papers do not fulfill multiple eligibility criteria. The remaining ten papers are included in the review. Fig. 2 visualizes the process of identifying and screening the sources. The subsequent review is guided by the target criteria defined at the beginning of this chapter.

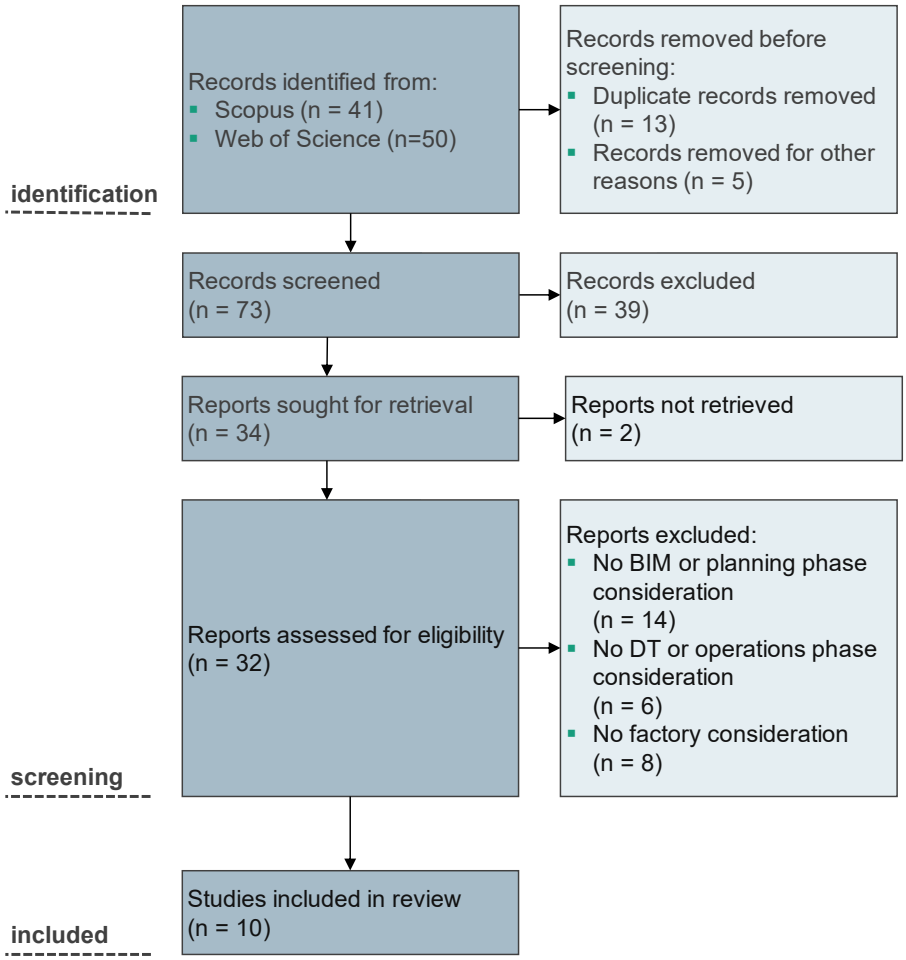


Fig. 2 Inclusion of sources into the literature review based on the PRISMA method

Three of the remaining sources are literature review studies:

- *Badenko et al.* [50] explicitly explore the integration of BIM and the DT for factories. Yet, their focus lies on the improvement of sustainability through enhanced data operability and optimized resource efficiency. The actual integration of BIM and the DFT in factories is not further investigated.
- *Raap et al.* [51] explore the impact of emerging technologies for factory planning. The authors identify BIM as relevant for the planning phase and the DFT as relevant source of real-time production information in the operational phase. The study remains at a high level and does not specify how these technologies could be integrated to realize cross-life-cycle DIC.
- *Schröder et al.* [52] analyze how HDFMs are currently applied across the two domains of building and production systems. The authors identify BIM as relevant for planning phase and the DFT as relevant for the operational phase. However, their further analysis concerning DIC focusses on the planning phase. The study results include the finding that only two (5%) of the sources within their analysis describe DIC in

detail. However, these works describe DIC within the planning phase only and neglect considering cross-life-cycle DIC between BIM and DT.

Amann et al. [53] and *Hellmuth et al.* [54] recognize cross-life-cycle DIC as an important need and identify DIC via HDFMs as a suitable solution approach. Nevertheless, they each focus on the interface between design and construction sub-phases within the planning phase. Accordingly, they do not consider the operational phase and the DT. They also spotlight the building domain, only considering the production systems domain as a peripheral topic.

Three additional sources recognize the need to integrate data from BIM and the DT, without describing or demonstrating this integration:

- *Badenko et al.* [55] and *Schäfer et al.* [56] each propose a framework of "factories of the future", which is mainly based on the integration of data from factory planning and operations. They both mention BIM and the DT as relevant data sources to be integrated. They also each recognize the need to integrate both geometrical and alphanumerical information in this DIC. However, neither *Badenko et al.* nor *Schäfer et al.* describe or show how this integration can be realized. Instead, they each outline this integration as a future research objective.
- *Bolshakov et al.* [57] discuss that the integration of resource-related BIM data and DT data is a prerequisite for integrating resource-related and additional process-related data in the operation of factory buildings. In their work, they propose a method for integrating BIM data and additional data, modeled in accordance with the Model Based Systems Engineering (MBSE) methodology. The authors do not further specify the integration of BIM data and DT data. Moreover, the focus lies on facility management within the operational phase. The relation to cross-life-cycle DIC in the context of factory replanning is not considered.

Two sources conceptually describe and prototypically implement data integration from Factory-BIM in the planning phase to the DFT in factory operations:

- *De Marchi et al.* [58] describe an approach of using Product Lifecycle Management (PLM)-systems as a CDE to realize cross-life-cycle DIC within learning factories. Their approach includes the integration of BIM from the planning phase and the DFT from the operational phase. However, the main goal lies in using the planning data in the operational phase where it is linked to real-time data. The authors explicitly focus on a greenfield use case of a learning factory, demonstrating a one-off information transfer from planning to operations. The continuous updating of the planning data within the PLM system based on the DFTs real-time data for factory replanning is not part of their research.

- *Luber et al.* [59] also address the subject of DIC in the factory life cycle at the interface between the planning and operations. The authors primarily focus on the technical feasibility of an interface between Factory-BIM models in the IFC standard and the DT in the AAS format. In the context of a laboratory study, they conceptualize the transfer of information from Factory-BIM models to a DT. However, they do not utilize a CDE. Additionally, the authors only address the interface between the planning and operational phases one-sided, avoiding considering updating the planning data in operations and utilizing it for subsequent replanning. In their outlook, they explicitly mention the need of future research to identify information objects to be transferred at the interface between Factory-BIM and DT. They also conceptualize the possibility to update Factory-BIM models based on the data generated within the DT.

Neither *De Marchi et al.* nor *Luber et al.* specify the information objects to be transferred or the relationship of this information objects to use cases.

It can be concluded that cross-life-cycle DIC with information logistics across the three fundamental technologies (BIM, HDFM in a CDE, and the DFT) has not yet been achieved. Existing works regularly recognize the need to realize this DIC, without proposing methods or systems to implement it. Solely the works of *De Marchi et al.* and *Luber et al.* conceptually describe the transfer of Factory-BIM models to a DFT. In this context *De Marchi et al.* demonstrate that a PLM-system can be applied as CDE and *Luber et al.* propose IFC and the AAS as relevant open data-standards to be integrated. However, the authors neither address the updating of planning data based on the operational data nor consider the utilization of this updated database for factory replanning.

In particular, the research gap lies in the lack of a comprehensive approach that ensures continuous and bidirectional information flow across the entire factory life cycle. This includes the integration of planning information within HDFMs on a CDE, as well as the seamless synchronization and updating of data with the DFT to enhance the efficiency of short-cycled factory replanning. Therefore, this paper aims to develop a method for DIC in the context of short-cycled factory replanning. Building upon previous research from *De Marchi et al.* and *Luber et al.* the proposed method should include the utilization of a PLM-system as a CDE and the utilization of the open data standards IFC and AAS.

4
Scientific Approach

The methodological approach to develop this method includes identifying information generated throughout the planning phase and stored in the Factory-BIM model as part of the HDFM in a CDE that can be used in the operation phase to create a Digital Factory

Twin. Furthermore, it includes identifying information generated throughout the operation phase in the DFT that can be used to update the HDFM from the planning phase for the following replanning cycle. As this information strongly depends on the specific use case, relevant use cases are gathered through a structured literature review in the first step. However, as previous research has often not adequately specified use cases and linked information, an expert study is conducted to improve the database, upon which the method is being developed. Therefore, experts from both academia and the industry are interviewed. Subsequently, key statements are extracted from the transcribed expert study. Specified use cases and information from the literature review and expert study are integrated into a shared list. Following the derivation of the specific information at the interface between planning and operation and vice versa, they are mapped into a shared information matrix. Based on the derived use cases, a concept for information logistics can be evaluated. Finally, the combination of the information logistics concept and the information matrix forms the basis upon which the method for DIC in the context of short-cycled factory replanning can be developed. This scientific approach is summarized in Fig. 3.

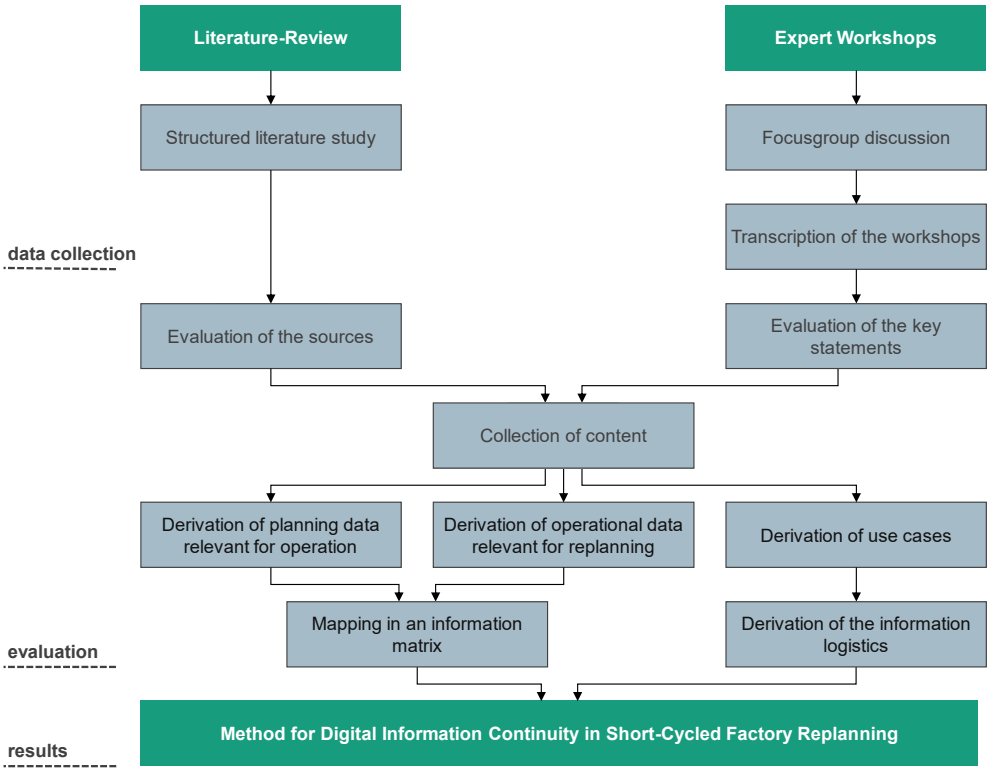


Fig. 3 Scientific approach

5
Data Collection and Evaluation

A structured literature review was conducted, distinguishing between the use case-specific data required for developing a DT during the planning phase and the data generated by the DT that is relevant for re-planning processes.

The two relevant preliminary works identified within the literature review (Chapter 3) offer only an abstracted view: Neither *De Marchi et al.* nor Luber et al. describe a specific use case. *Luber et al.* mention to link several specific information objects (energy demand, technical gas demand and availability). *De Marchi et al.* do not specify information objects.

In addition to the analysis of the literature sources, an expert study was conducted. This study followed the inductive, qualitative focus group discussion methodology, which is beneficial for gaining in-depth insights into a relatively new and complex research area [60]. A total of ten experts participated in two separate discussions, each lasting one hour. The sociodemographic background of the participants is listed in Appendix A.1. While the typical number of participants for focus group discussions is typically 2–21 per session [60], the number of participants in this study falls within the lower third of the typical range. According to the literature, more focus group sessions should be conducted until theoretical saturation of the results is reached [61]. In their meta-study, *LaNoue et al.* demonstrated that combining two sessions in each of their experiments yielded over up to 90% of the maximum achievable insights, thereby providing evidence of saturation [62]. In the present case, a significant overlap of over 70% between the findings of the first two sessions could also be observed, which led to the decision not to schedule any additional sessions.

Within the workshops, information objects were collected separately for the two roles of the production system operator and the building operator. These personas were chosen to represent the two organizational domains, production and building, because they are highly separated in practice and use cases for the DFT, and the associated information requirements therefore differ [15]. A detailed table listing the identified exemplary use cases can be found in Appendix A.2. Due to the heterogeneity of individual applications in factory operations, providing a comprehensive list of use cases for the DFT is infeasible. Therefore, the list of use cases is primarily intended to facilitate the choice of a suitable use case for the subsequent validation of the methods applicability. As a result of this heterogeneity, the data collection process focused on the two widely used data sources, energy monitoring and MES [6], which were also indicated by *Luber et al.* as relevant. A close examination of the use cases related to the energy

monitoring system reveals a strong focus on consumption-oriented optimization in the domains of production systems and buildings. The majority of the identified use cases are oriented towards reducing energy consumption and costs. These use cases include, for instance, identifying peak loads or improving energy efficiency. Exceptions to this general rule include sustainability reporting and bottleneck analyses, among others. Conversely, the use cases for the MES demonstrate a more varied array of applications. In addition to monitoring current states or parameters, the use cases in this area are more strongly focused on planning aspects. The data and information collected during operation are intended to provide a more quantifiable basis for future processes, such as maintenance and repair measures or capacity planning.

The heterogeneity of use cases underscores the importance of a flexible and adaptable method for ensuring DIC in factory planning and replanning. Moreover, the use cases, in combination with the fundamental underlying technologies (Chapter 2), assist in deriving a concept for appropriate information logistics. Fig. 4 illustrates the information logistics schematically (for detailed information logistics see Fig. 7).

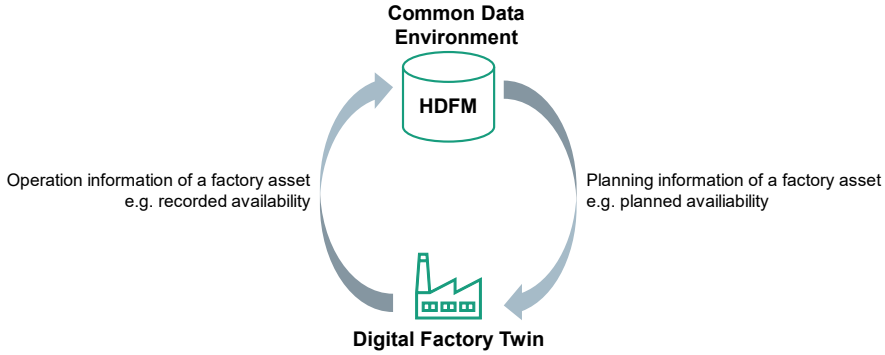


Fig. 4 Schematic concept for cross-life cycle information logistics with HDFM and Digital Factory Twin

Upon finishing the planning process and generating the HDFM in the CDE, the DFT is provided with planning-relevant information. In this context, an example would be the planned availability of an asset. During factory operations, supplementary operational data regarding the asset, including its actual recorded availability, is generated within the DFT. At the initiation of the subsequent replanning cycle, this operational information is transferred back to the HDFM in the CDE, thereby establishing an updated basis for factory planning.

However, as the information objects are highly use-case-dependent and preliminary works do not address this topic sufficiently (see Chapter 3), a generalizable use-case-specific information selection procedure is needed when developing a new method for cross-life-cycle DIC.

Based on a use case, specific operational data is of interest for factory replanning, precisely the information that serves as parameters and constraints for system dimensioning. Typically, such information is estimated during the planning phase, for example, in simulations [63], and subsequently monitored during operation through Key

Performance Indicators (KPIs) within the DT [64]. These KPIs are defined in accordance with ISO 22400-2 [65] for production-related metrics and ISO 50006 [66] for energy-related metrics. As these KPIs already define the DIC between DFT and the following replanning phase, the remaining intersection of information that is relevant to both the planning and operation phases of developing a DT is of interest.

For the structuring of this information, the authors decided to use a comprehensive matrix and drew on the information classes defined in ISO 23247-3 [67]. Yet, the information classes "Equipment", "Building Services", and "Environment" are listed twice to differentiate between the information that can be directly represented in the Factory-BIM model and the information that is available as supplementary data in the HDFM in the CDE. Six information types are introduced to further refine the information, distinguishing between descriptive, geometric, process, media, relational, and other technical information.

Each cell in the information matrix represents a combination of information class and information type, including an indication of whether the information is stored directly in the Factory-BIM model or in the CDE. It is conceivable for multiple information objects to exist for a given combination of information class and type. Conversely, it is also possible for specific combinations to have no associated information, resulting in empty cells in the information matrix. Fig. 5 schematically illustrates the structure of this information matrix, including exemplary information objects. This information matrix is also utilized to structure the information objects gathered in the expert workshops.

Information type	Factory-BIM model			Holistic Digital Factory Model in CDE						
	Production equipment	Building infrastructure	Environment	Production equipment	Building infrastructure	Environment	Workforce	Product	Material	Additional documentation
Descriptive information	Type ID	Type ID	Zone ID	Type ID	Type ID	Zone ID	Personal ID	Type ID	Type ID	Document-ID
Geometric information	Spatial location	Spatial location	Spatial location				Workstation	Storage location	Storage location	
Process information	Inventory	Incline	Minimum set temperature	Distribution of downtime	Safety information	Safety information	Shift schedule	Scrap (per production process)	Disposal information	
Technical utility information	Max. power consumption	Network frequency			On-site energy generation			energy consumption per production quantity		
Relationship information	Assignment consumers to supply area	Assignment consumers to supply area		Information flow	Information flow	Information flow	Collaboration	executing resources per process step	Required transport pathways	
Technical information	Maintenance interval	Perimeter for external elements	Illuminance	Installation instructions	Installation instructions	What-if scenarios	What-if scenarios	M-BOM	Procurement plan	Scheduled revision times

Fig. 5 Schematic structure of the information matrix with exemplary information objects

While compiling a complete list of all information in each cell is impossible, the authors have collected all information derived from the literature review and expert workshops in this matrix. However, the most relevant results are:

1. A substantial proportion of the information inquired by the production system operator is drawn from KPIs known from production planning and control. This KPIs include planned lead time, throughput, availability, and scrap rates. Moreover, there is an increasing emphasis on energy-related information and data aimed at equipment maintenance.

2. For the building operator, energy-related information is less relevant. Conversely, aspects such as installed materials, warranty periods, and material disposal are emphasized. Hence, the building operator focuses more on maintenance and servicing-related information.
3. Information objects such as Type ID, years of use, and safety management are pertinent to both the production system operator and the building operator.

6
Method for Digital Information Continuity in the Context of Short-Cycled Factory Replanning

Based on the information matrix and the schematic concept of information logistics (Chapter 5), combined with the objective vision (Fig. 1), a novel method for DIC in the context of short-cycled factory replanning can be formulated.

The initial step is the *provision of planning information*, which accompanies all factory planning phases covered, ranging from goal definition to the completion of detailed planning. Given the increasing relevance of BIM models in factory planning, the Factory-BIM model serves as the central, overarching planning information upon which the method is based. Subordinate planning information is, as a result, directly integrated into the Factory-BIM model, provided that it can be meaningfully represented as alphanumeric data. To ensure the comprehensive execution of the methodology, the information obtained during the third step of the method must be made available as the final planning information. Moreover, the selection of appropriate exchange formats must be made during the planning phases, as incompatibilities between exchange formats in the fourth step (during the creation of the DFT) could result in significant additional effort. Following *Luber et al.*, standardized exchange formats, such as the IFC format, are recommended during the planning process. Finally, all planning information that has been generated is stored in HDFM in a CDE.

The second step involves the *selection of use cases for the Digital Twin*. Given the significant reliance on specific use cases in determining the necessary information for developing a DT [68], this selection process is of fundamental importance. The list of exemplary use cases (A.2, Fig. 15 + Fig. 16) can serve as a guideline in this process.

The subsequent third step entails the *definition of relevant information objects*. All planning information necessary for developing the DFT is selected in this step. In addition to choosing the necessary information objects, defining the corresponding exchange formats is essential to ensure DIC. This definition is contingent upon the particular use case of the DFT and the associated IT landscape, making it impossible to determine universally. As the planning information at this stage is stored in the exchange formats

defined during the planning phase within the HDFM on the CDE, the selection of exchange formats is essential.

The fourth step is the *development and operation of the Digital Factory Twin*. The DFT is initially created using information from the planning phase during this step. Information selected for use cases is retrieved from the HDFM in the CDE. Depending on the exchange format in which this information is available in the HDFM in the CDE, and the exchange format chosen in the third step, a transformation may be necessary at this stage. Since transforming information into different exchange formats can disrupt digital continuity [69], the importance of selecting the right formats in the previous step becomes apparent. Once the DFT is established, it can be used in factory operations. The DFT is continuously enriched with real-time operational data collected during factory operations.

The fifth step, *provision of relevant operational information,* is triggered by initiating a factory replanning. However, continuously extracting operational information during factory operations also appears beneficial for monitoring production. This information is transferred from the DFT to the HDFM in the CDE in the form of KPIs. Additionally, the current state of the Factory-BIM model, which reflects the realized factory as an LOD 500 model (as-operated), is transferred to the HDFM in the CDE. Ideally, the Factory-BIM model is updated during factory operations to reflect geometric changes, ensuring it represents the factory's current state when replanning is initiated. As in the third step, relevant KPIs and exchange formats are selected. KPIs are selected based on the use case and the information generated by the DFT. KPIs considered irrelevant to the replanning project can be excluded in advance. The selection of exchange formats must also be based on the DFT's IT landscape. Finally, the operational information is stored in the HDFM in the CDE in the selected exchange formats. This information includes the Factory-BIM model and KPIs captured by the DFT.

Project-specific replanning measures are defined and detailed during the sixth step of *replanning*. Triggers for factory replanning are typically event-based managerial decisions concerning the product portfolio, technologies or the volume mix [2]. To this end, operational information is consolidated within the HDFM in the CDE. Specifically, the KPIs in the Factory-BIM model from the planning phase are updated with the actual KPIs determined during operations using the DFT. This approach allows for replanning based on current models and information, eliminating the need for manual updates to the initial planning.

Similar to the first step, the seventh step involves the *provision of replanning information* in the HDFM within the CDE. This information is generated during the replanning process, so steps six and seven of the method mainly run in parallel. Because not all replanning information can be provided until the last information object has been

generated, this step occurs partly sequentially after the replanning process in the method.

Once all of the replanning information has been stored in the HDFM within the CDE, the method allows continuation at two different points. If the use cases, and thus the information required for developing the DFT, remain unchanged from the initial selection, the process continues with the fourth step. Otherwise, the method reverts to the second step, which involves renewing the selection of use cases for the DFT. This iterative cycle can be repeated as necessary. Additionally, at each iteration, a decision can be made as to which of the two points in the method the process should continue. Fig. 6 visualizes the described steps of the method and their interconnection through the HDFM in the CDE.

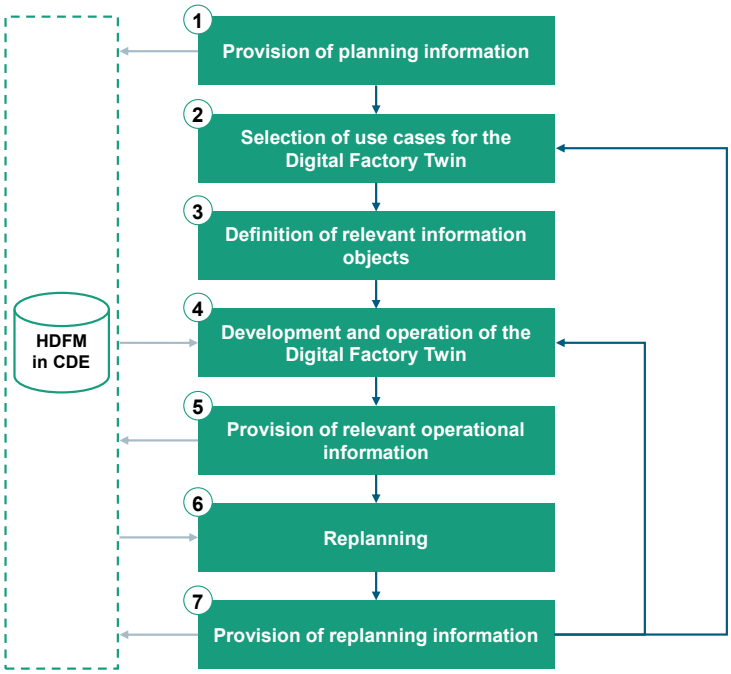


Fig. 6 Method for DIC in the context of short-cycled factory replanning

Combining the steps of the method (Fig. 6) with the schematic concept of information logistics (Fig. 4) yields the detailed information logistics of the method. The Factory-BIM model and the additional planning information collectively constitute planning information in the HDFM within the CDE. Then, the relevant planning information is transferred from the HDFM in the CDE to the DFT. This information forms the initial values of the DFT and can be adopted later. Simultaneously, information generated from factory operations in corresponding information sources is integrated into the DFT, e.g. by utilizing the AAS format. Based on this information KPIs are continuously calculated and possibly visualized in the DFT.

Once the replanning process is triggered, replanning information is extracted. This information consists of the "as-operated" Factory-BIM model and relevant KPIs. These are stored as operational information in the HDFM within the CDE. KPIs belonging to the

information classes in the Factory-BIM model can be transferred into it. Any discrepancies between the extracted Factory-BIM model and the actual factory must be incorporated into the model. Such discrepancies may arise if the "as-built" Factory-BIM model is not continuously updated during factory operations. The updated Factory-BIM model and the remaining KPIs serve as operational information for replanning.

As in the planning phase, replanning information is provided in the HDFM within the CDE in the form of a Factory-BIM model and additional replanning information. These constitute the replanning information. At this stage, components of the Factory-BIM model and additional replanning information relevant to developing and using the DFT can be utilized.

The information logistics illustrate the flow of information and the data transferred, which interconnect the individual steps. Exchange formats are not specified, as no universal specification can be provided. Yet, the IFC format can be mentioned as an example for the Factory-BIM model, and the CSV format for the additional planning and replanning information. This detailed information logistics flow is visualized in Fig. 7.

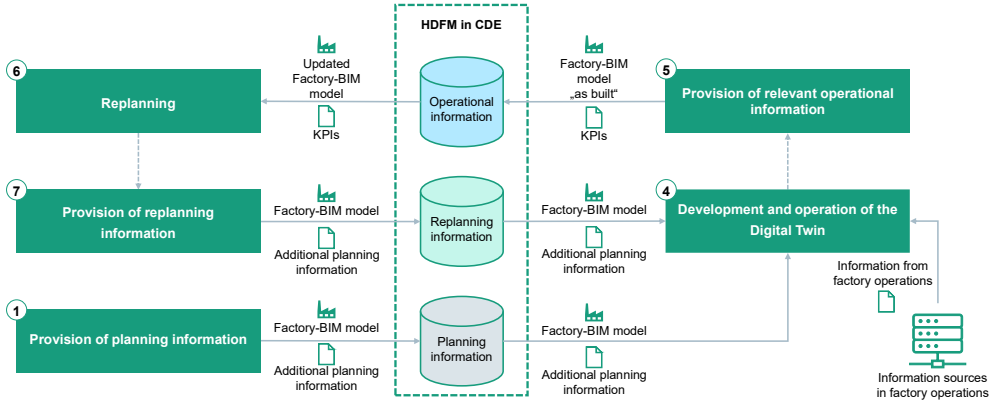


Fig. 7 Detailed information logistics within the steps of the method

7 Validation of the Feasibility on the Application Scenario of a Laboratory for Additive Manufacturing

The IGCV-Laboratory for Additive Manufacturing is used to validate the applicability of the developed method. Due to its primary use as an experimental factory hall, it does not represent a traditional factory. Instead, it consists of many different production machines that do not have direct relationships with each other. Constantly changing research topics demand regular replanning of the laboratory. Therefore, it forms an ideal application scenario for short-cycled factory replanning. As the process of initial operational data acquisition involves high manual efforts, only one production machine within the laboratory is used to apply and validate the applicability of the developed method.

Before the application, a few preparatory measures must be carried out. These include incorporating the relevant attributes within the Factory-BIM model and creating a fictive production schedule. The Factory-BIM model with the production machine and the building is depicted in Fig. 8.

Upon the basis of this application scenario, the method can be applied. However, seven steps of the method are executed only once due to the redundancy of the closed-loop approach.

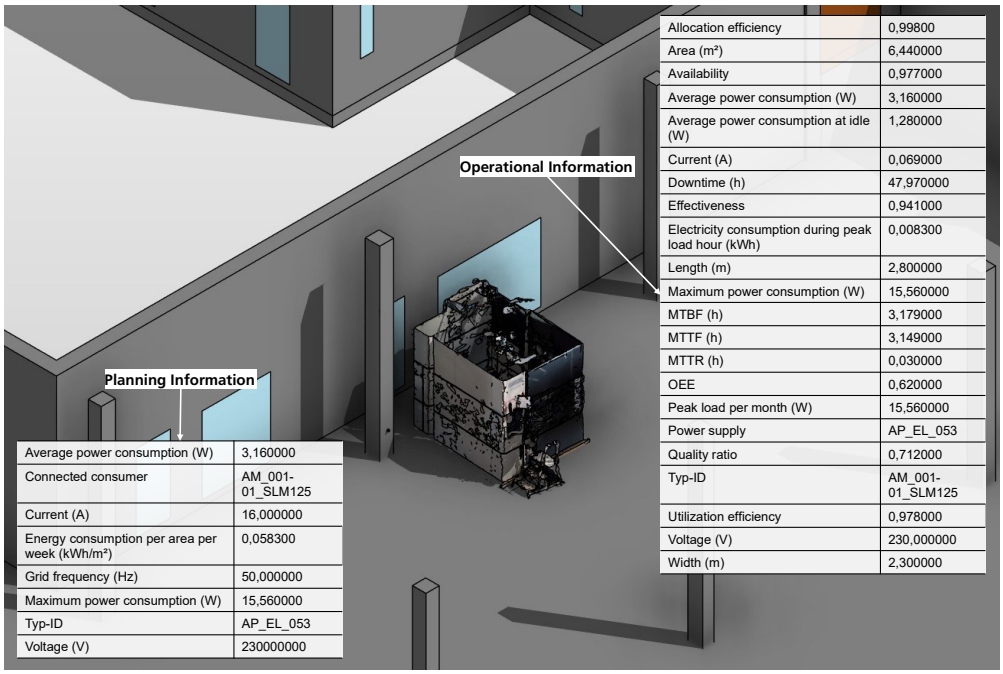


Fig. 8 Factory-BIM Model for the application scenario in Autodesk Revit

The first step involves providing the planning information in the HDFM on the CDE. This includes uploading the Factory-BIM model in the IFC format and the schedule in the CSV format to the HDFM on the CDE. In the second step, use cases of the DFT have to be selected and further detailed to identify the needed information with the help of the information matrix. To validate the applicability of the method, two use cases of the DT are selected. The first use case is the visualization of the energy demand of the production machine in defined time intervals based on recorded sensor data. The second use case of the DFT is the monitoring of the OEE and the machine state, including their influencing factors. This use case relies on the machine's status data.

With these DFT use cases defined, the necessary planning information for developing the DT can be identified in the third step. The required information mainly includes attributes from the Factory-BIM model (Fig. 8). It is important to note that some attributes are also linked to the media supply interfaces of the building. Only the schedule forms an exception, as it cannot be implemented in the Factory-BIM model and is associated with the additional planning information. For the DFT use cases, three KPI's are relevant to visualize the energy demand, especially attributes describing the media supply and requirements. Production KPIs are needed from the Factory-BIM model to develop the

DFT of the second use case (Fig. 8). Additionally, the schedule is essential to match the actual order sequence and duration with the planned values. For the Factory-BIM model, the IFC format, and for the schedule, the CSV format is chosen as the exchange format. Therefore, no further conversion of the planning information is necessary.

A DFT was created in the **fourth step** using a CDE solution as an open and modular platform technology based on the various partial models available (in this case, using a continuous IFC data chain in the Contact Elements CDE). The model shown in **Fig. 10.1** is the baseline and includes the building, the production system, media supply interfaces, and other peripheral devices required for production in the factory. As shown in the previous sections, the KPIs for subsequent implementation in operation are located within the IFC metadata. Once the as-built Factory-BIM model has been released on the CDE, these KPIs are automatically extracted from the integral model and automatically imported to the asset (the DFT of the building in operation). For this purpose, no proprietary exchange formats are used. After extraction from the IFC model, the relevant data is attached to the classification of the asset and displayed in a human-readable format on the user interface for further analysis (**Fig. 10.2**). At the same time, this data is also available in standardized exchange formats such as the AAS in accordance with the IDTA 01001-3-0-1 [70] via the CDE Representational State Transfer Application Programming Interface (REST API). In this way, the data can not only be transferred internally within the CDE but also shared explicitly with other external stakeholders within the value chain throughout the asset's lifecycle (such as with external contractors in the replanning case described above). After the data has been transferred and the asset instantiated as a DFT (**Fig. 10.3**), the Factory-BIM models required for replanning can be further enriched based on the transparent and robust data information chain in the **fifth step**. In this case, dashboards within the CDE were used to visualize to planned KPIs and compare them to the actual KPIs from factory operations. These dashboards are shown in **Fig. 9**. The left dashboard visualizes energy-related KPIs and the right dashboard production-related KPIs. Planned values are colored green and actual values green.

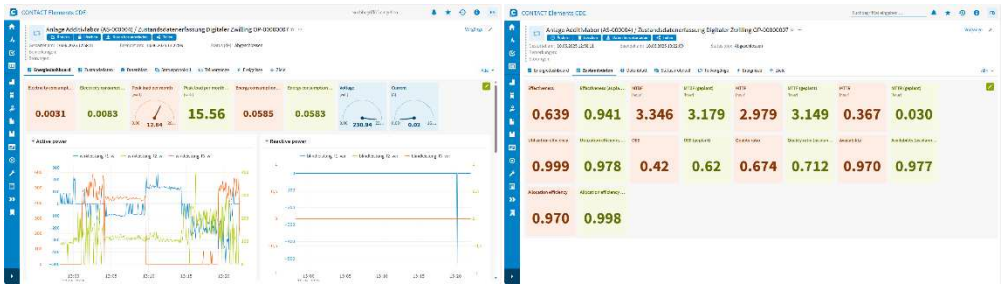


Fig. 9 Dashboards for comparing planned KPIs to the actual KPI values

Specifically, in this application scenario, a second additive manufacturing machine is needed due to low OEE KPIs and increasing production volumes. This triggers a

replanning (**sixth step**). Finally, the replanning information and the associated models are shared and released on the CDE using defined workflows (**seventh step**).

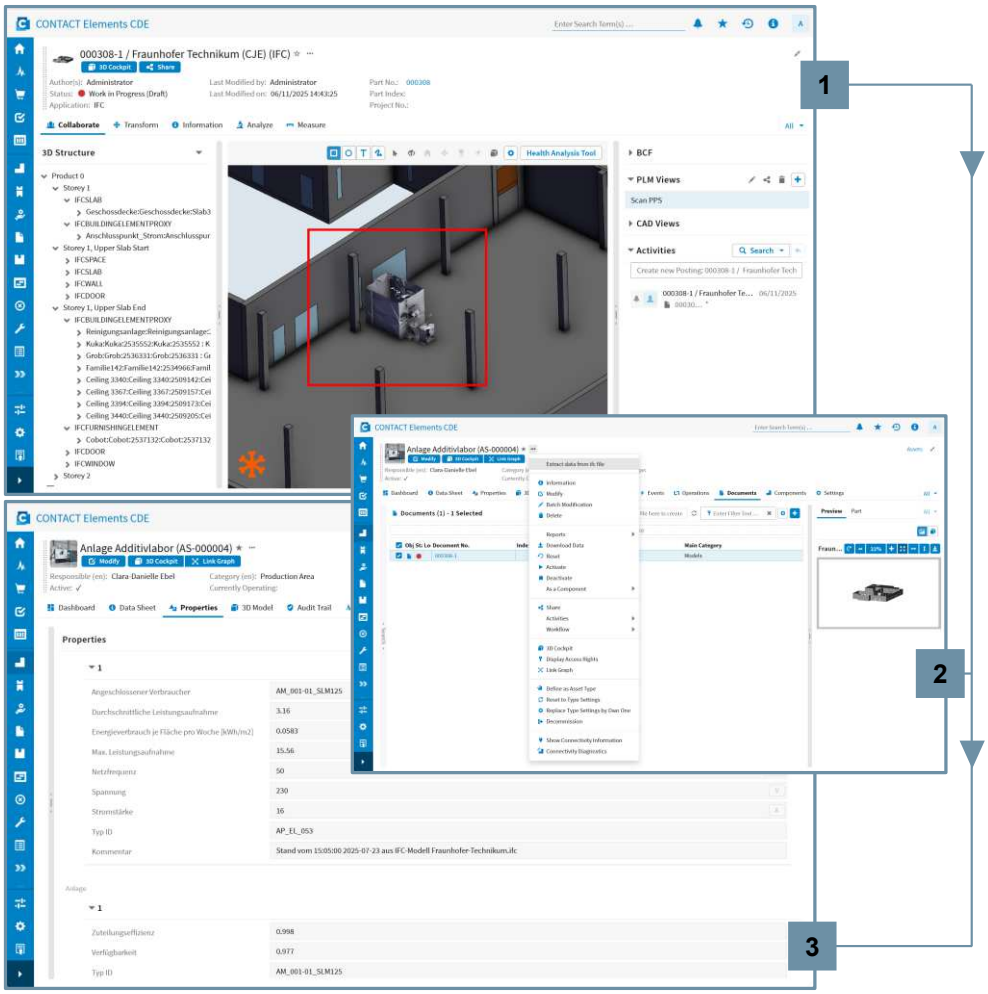


Fig. 10 Implementation of HDFM and DT on the Contact Elements CDE

To further validate the applicability of the developed method, an objective proof that the method meets the requirements of the intended application must be provided [71]. In this context, the information transported along the interfaces between planning and operation, and operation and replanning is considered. This approach is used because these two interfaces represent the critical point concerning DIC. The transported information is separated into directly and indirectly transported and lost information. Directly transported information can be used in the following instances without manual conversion steps, whereas indirect information must be transferred manually. Regarding DIC, the direct transport of information represents the ideal case. On the other hand, the worst case is the loss of information, which cannot be used in the following instance. For the interface between factory planning and operations, 96% of the information is transported directly, with 4% not being transferred into the operation phase and therefore counted as lost information. Along the interface between factory operations and replanning, the largest share of information, with 67% is transported indirectly, and

only 5% is transported directly. 28% of the information is useless for the replanning phase and therefore lost. The evaluated DIC for both interfaces is visualized in Fig. 11.

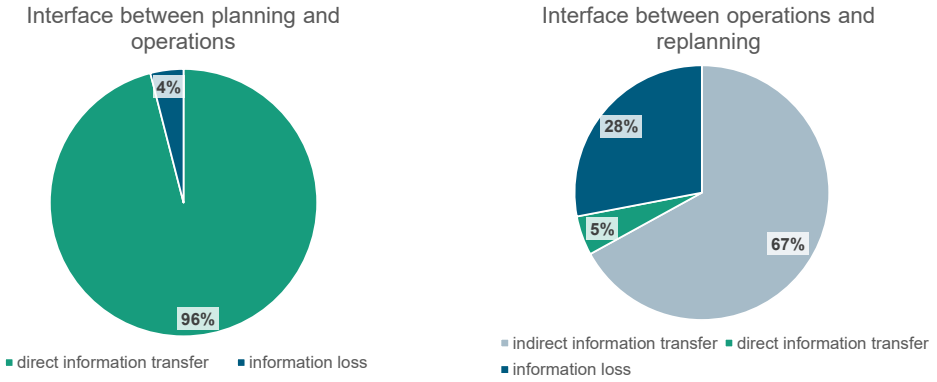


Fig. 11 Evaluation of DIC at the interfaces between the factory life-cycle phases

8 Discussion

The following discussion will address the aforementioned results, critically reflecting the low level of automated data transfer for the interface between factory operations and replanning, analyzing the generalizability and comparing them with the existing state of the art.

8.1 Missing functionality for automatic Factory-BIM model updating

The interface between factory planning and operations offers good results regarding DIC. This is because alphanumeric information from the Factory-BIM model is extracted and directly implemented into the AAS. Only the schedule can not be implemented into the DT, representing lost information.

The information at the interface between factory operations and replanning is mainly transported indirectly because there is no functionality implemented into the CDE to automatically update the alphanumeric information in the Factory-BIM model with the information from the AAS. Because the operation data needed for the replanning phase consists only of the "as built" BIM model and the relevant KPI's, additional information gathered in the DT, e.g., comments or graphs, is lost information.

Even if information transfer is manual (indirect), due to the missing CDE functionality, DIC is demonstrated. It can be concluded that the developed method meets the requirements of DIC along the interface between factory planning and operations. On the other hand, the interface between factory operations and replanning offers potential to be optimized through automation. This potential lies in a functionality within the CDE that automatically updates the Factory-BIM model with the information in the AAS and could increase the directly transported information share to 72%. As the 28% lost

information is not needed for factory replanning, theoretically, a DIC of 100% is demonstrated.

8.2 Generalizability of the Method to Other Factories or Production Systems

Although the validation of the proposed method was conducted using a single production machine within a research laboratory, the authors argue that the method is generalizable to other factories and more complex production systems. This claim is supported by the broader implementation within the research project FaBIM, where an entire battery cell factory was successfully modeled in an HDFM on the CDE.

The authors therefore currently perceive no fundamental limitations to the application of the method to other factories, provided that the same data standards are utilized. However, a potential challenge exists in the standardization of Factory-BIM models within the IFC framework. At present, the IFC standard does not fully support the representation of all aspects of production systems. To address this issue, the authors are actively contributing to working groups under the umbrella of *buildingSMART*, the objective of which is to extend the IFC standard to include factory-specific objects. Recent advancements include the publication of initial classes for functional areas and logistics pathways, with ongoing efforts to define equipment classes. These advancements are expected to further enhance the applicability of the method to a wider range of industrial contexts.

8.3 Comparison to the State of the Art

The proposed method represents a significant advancement in the field, addressing critical gaps in DIC across the factory lifecycle. Existing works from *De Marchi et al.* and *Luber et al.* [59], primarily remain at a conceptual level, focusing either on learning factories on a general level or the one-off technical feasibility of information transfer of Factory-BIM models in the IFC standard to DFTs in the AAS format. While these contributions provide valuable insights into the potential of integrating BIM and DFT technologies, they do not concretely address the specific requirements of cross-life cycle DIC at the interfaces between factory planning, operation, and replanning phases. Additionally, the correlation between DFT use cases and the information exchanged at these interfaces was not considered in the past. In contrast, the proposed method considers DIC and its technical realization through the HDFM within a CDE. The method is grounded on the definition of specific information objects and exchange formats, thereby ensuring a structured and software-independent approach. Furthermore, the method explicitly links DFT use cases to the information required at the interfaces, thereby addressing a key research gap identified in prior works.

The method also tackles the challenges associated with the standardization of Factory-BIM models in the IFC format. A small number of comprehensive standards for representing production systems in IFC has been identified as a limitation in previous works. To address this gap, authors have proactively contributed to *buildingSMART* working groups with the objective of extending the IFC standard. Recent advancements demonstrate the pragmatic viability and prospective scalability of the method.

Moreover, the proposed method bridges the gap between conceptual frameworks and practical implementation, offering a solution for achieving DIC across the factory lifecycle. This work builds upon the existing literature (utilization of PLM-systems proposed by *De Marchi et al.* and utilization of IFC and AAS open data standards proposed by *Luber et al.*) while also significantly extending the state of the art by addressing both technical and methodological challenges.

8.4 Data quality and correctness

Another limitation of the proposed method is that it is grounded upon the prerequisite of reliable or correct data. The continuous monitoring of data quality across the factory planning project and within factory operations to identify anomalies is therefore a key fundamental requirement for the successful application of the method proposed within this paper. Ongoing research within this field will consequently enable broader applicability of the proposed method.

9 Conclusion and Outlook

This paper introduces a new method for achieving cross-life-cycle DIC in the context of short-cycled factory replanning. The proposed method addresses the critical challenges of information transfer at the interfaces between factory planning, operation, and replanning. These interfaces are increasingly relevant due to shorter replanning cycles in demanding industrial environments.

The scientific approach involved the derivation of DFT use cases and information logistics, as well as the identification of information to be exchanged at life cycle interfaces. This objective was based on data collection through a dual approach of a comprehensive literature review and expert workshops. The method utilizes existing technologies, such as Factory-BIM models for planning and DFT for operations and demonstrates how a HDFM within a CDE can bridge these technologies. Specifically, the method enables the use of planning data to establish a DT during operations and facilitates the update of the HDFM in the CDE based on KPIs generated by the DFT.

The applicability of the method was validated using a real application scenario in the IGCV Additive Manufacturing Laboratory. The findings indicated a DIC of 96% at the interface between factory planning and operations, as well as 72% at the interface from operations to planning. As the 28% lost information is not required for replanning, a DIC of 100% at this interface is demonstrated. However, due to capacity constraints within the project, the implementation of automated functionality for updating the Factory-BIM model during operations was not feasible. The findings indicate that 100% direct information transfer might be attainable at the interface between operations and replanning for this application scenario, under the condition that the functionality in question is successfully implemented.

These findings represent a significant advancement beyond the current state of the art and have the potential for generalizability to other factories and production systems. Nevertheless, the standardization of information within Factory-BIM models remains a challenge. The authors are currently engaged in efforts to expand the IFC standard for factory-specific objects through initiatives spearheaded by *buildingSMART*, with initial success already achieved.

Following research activities may cover the exploration of further use cases for the DFT, including the potential for updating work plans based on process time evaluations. This could lead to significant enhancements in operational production planning and strategic factory replanning. Additionally, the geometric updating of the HDFM remains an area of research that has not yet been fully explored, with initial advancements already being made in related projects at Fraunhofer IGCV. Consequently, a methodology is required to assess the cost-benefit trade-offs associated with the continuous updating of the HDFM during factory operations. While the implementation of continuous updates has been demonstrated to reduce effort during replanning and accelerate the initiation of production, it has also been shown to introduce operational costs.

Declaration of generative AI and AI-assisted technologies in the writing process

While preparing this work, the authors used Artificial Intelligence (AI) to revise, shorten, and streamline their original manuscript. The AI tools were not used to generate scientific findings, conduct data analysis, develop the methodology, or draw scientific conclusions. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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Compliance with ethical standards:

- Competing interests
  The authors have no relevant financial or non-financial interests to disclose.
- Ethics approval
  This study involved focus group discussions with experts in the field of factory planning. As this was a non-interventional, purely qualitative data collection and did not involve medical research or experiments on human participants, formal approval by an ethics committee was not required in accordance with institutional and national guidelines.
- Informed consent
  All participants were informed in advance about the purpose of the study, the recording and transcription of the discussions, the scientific analysis, and the intended publication. They agreed voluntarily to participate. Verbal informed consent was obtained from all participants prior to the focus group sessions. All data was anonymized and no personal data was disclosed.

Author Contributions

Conceptualization (F.B.); Methodology (F.B., C.E.); Software (C.E., S.F.); Validation (F.B., C.E.); Investigation (F.B., C.E.); Writing - Original Draft (F.B.); Writing - Review & Editing (F.B., A.M., R.D.); Visualization (F.B., C.E.); Supervision (F.B., R.D.).

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Appendix

A.1. Sociodemographic Background of the Focus Group Participants

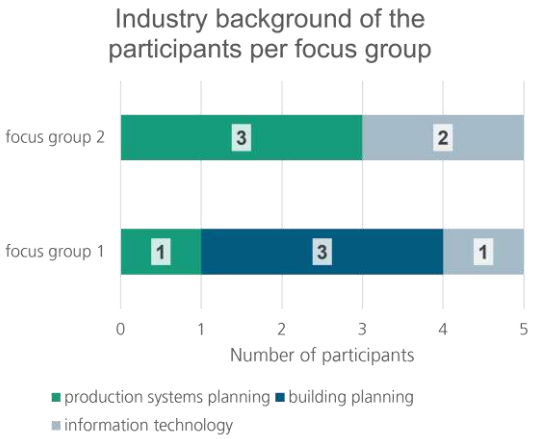


Fig. 12 Industry background of the focus group participants

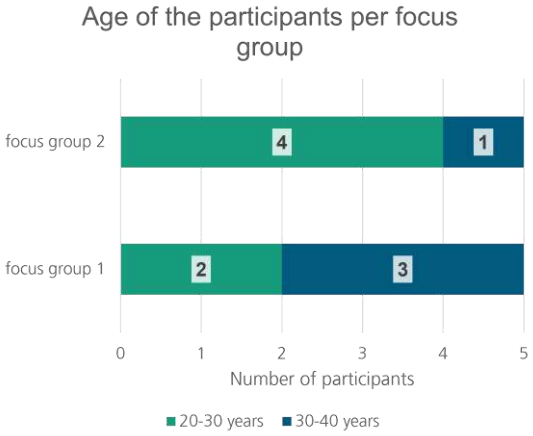


Fig. 13 Age of the focus group participants

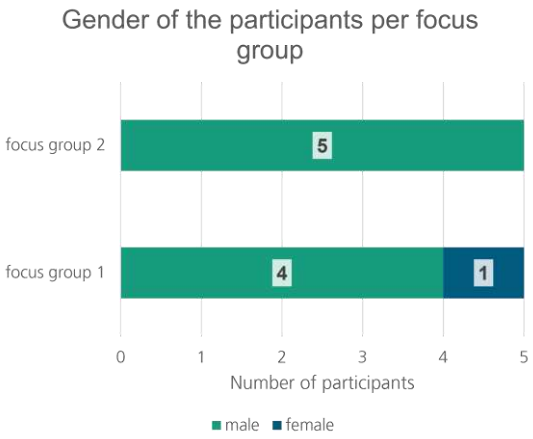


Fig. 14 Gender of the focus group participants

A.2. Use Cases

Energy MonitoringSysten		MES	
Production System Operator	Building Operator	Production System Operator	Building Operator
Support sustainability reportings	Investmens basis on the building KPI	Reduce downtimes	Consolidate maintenance processes with PPS
Energy flexibilzation (ePPS)	Reduce energy costs	Increase utilization	Predict possible failures
Improved production cost calculation through precise information on energy consumption	Make energy consumption visible, e.g. dashboard in lobby, to raise awareness in the company	Reduce scrap	Integration of building information into process planning
Basis for optimizing production processes	Coordnation/Optimization of heating and ventilation needs	Flexibilization of production processes	Plan spare parts and personnel proactively
Detect Energy saving potential	Betrieb der Assets (z.B. Lüftung) optimieren Optimize operation of assets	Predictive maintenance	Predictive maintenance
Optimiziation of energy consumption through identification of load peaks	Optimiziation of energy consumption through identification of load peaks	PPS	
	Reduce load peaks	Power supply	
	Optimization of energy consumption through control systems considering room usage	Tool and resource management	
	Optimize load profile of assets (e.g. ventilation system)	CIP (for identifying bottlenecks)	
		Worker support	
		Monitoring quality parameters	
		Vehicle and transport control	

Fig. 15 Exemplary use cases identified in the first group discussion

Energy Monitoring System		MES	
Production System Operator	Building Operator	Production System Operator	Building Operator
Peak load optimization	Peak load management	Real-time OEE montoring	Actual media consumption
Energy flexibilty (ePPS)	Peak load optimization	Quality management	Identification of cause-effect relationships
Reduce energy cost	Reduce energy cost	Predictive Maintenance	Predictive Maintenance
Optimize energy costs by adjusting procurement to variable electricity prices	Adaption of energy system design to production requirements (media supply, connections)	Condition Monitoring of plant conditions	Proactive media supply (process heat and cooling)
Design/selection of new production facilities under energy-related aspects	Monitoring und optimization of media supply	Capacity utilization optimization	Scheduling of building sevices maintenance (according to production needs)
Possibility to analyze the production system and derive targeted measures	Bottleneck analyses → identification of where additional facilities for resource provision are required: does the (locally) supplied amount of energy suffice to meet the production-related demands?	Quality management: analysis and control/regulation of production parameters with focus on quality	Future planning of production areas (brownfield/greenfield) -> size/layout of production areas
Decision support and facilitation of error identification in operational processes. Particular potential arises from the integration with data from other systems (MES, ERP). (e.g. when energy consumption during production downtime serves as an indicator of inefficient resource utilization)	Opportunities for the intelligent control of technical building services (TGA) systems of all kinds. In this context, it is first necessary to establish transparency, followed by the implementation of analytical and intelligent functions. The added value lies particularly in the integration and networking of data from different sources	Production planning and control: Subtasks include program planning and demand planning, with information requirements focusing on throughput and lead time (on an aggregated level and at the production system level). The subtask of detailed scheduling (of capacities and deadlines) requires information on throughput and lead time at a more granular level (on the resource level).	Targeted control of building functions aligned with situational production requirements
Recording of ecological indicators for production and the product (-> CO2 footprint, Digital Product Passport	Opportunities for cause-based allocation of resource consumption -> creating an economic lever and thereby providing incentives for the reduction of resources in the areas where consumption occurs.	Maintenance: Analysis and control/regulation of production parameters affecting equipment availability, predictive modeling of resources for the scheduling of maintenance activities and the procurement of spare parts	
	Reports (e.g. CSRD)	PPS	
	Identification of investments requirements	PPS improvement through more accurate data basis	
	Monitoring energy efficiency (input energy in relation to output)	Analysis of effectiveness/productivity incl. Influencing factors	
		Demand-driven provision of production resources	
		Ergonomics: person-specific and task-related workload	

Fig. 16 Exemplary use cases identified in the second group discussion