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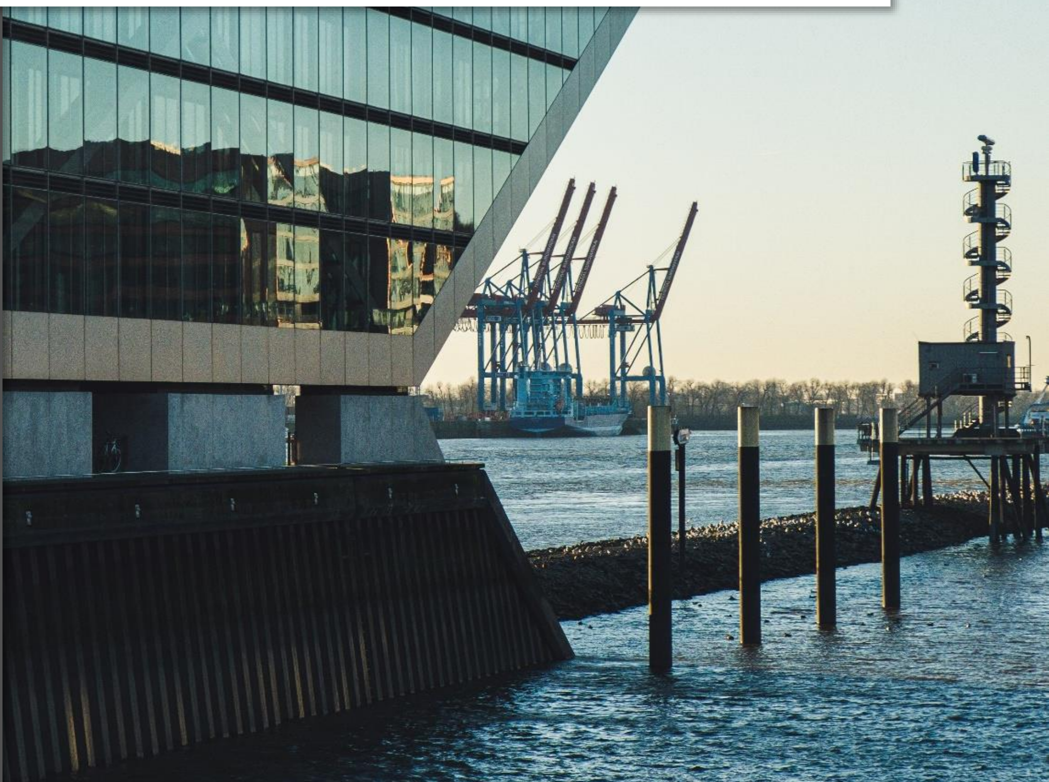

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Designing the Data Supply Chain of a Smart Construction Factory

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Purpose: *The purpose of this paper is to design a concept of the data supply chain of a smart construction factory by analyzing the information flow and Building Information Modeling (BIM) object data that are available through innovative identification technologies and communication systems. Furthermore, an appropriate system for controlling logistics processes is defined.*

Methodology: *The approach is developed using the Digital Twin Concept Model. In the first step, the examined use case is evaluated and compared with the digital twin fulfillment requirements. Subsequently, the data supply chain is designed considering the three attributes conceptualization, comparison, and collaboration.*

Findings: *The paper shows how the idea of a data supply chain of a smart factory can be transferred into the building industry. The digital core in terms of a data warehouse monitors material flows according to quantity, location and time and can help to pilot logistics processes.*

Originality: *Smart factory research has predominantly focused on production processes of the biggest industries, without taking the building sector and externally required logistics into closer consideration. However, significant changes are expected as a result of the European Green Deal, which will change the entire industry as well as related logistics.*

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1 Introduction

Industry 4.0 still inspires the manufacturing industries and leads to the introduction of new technologies every day. Driven by the fourth industrial revolution, companies are investing in the development of smart factories with the aim of integrating digitalization into fabrication structures (Ruile, 2019). By creating an autonomous production and logistics environment in which machines, systems and vehicles communicate independently with each other, companies hope to remove humans from manufacturing processes in order to operate more efficiently (Scheer, 2017).

Undoubtedly, the building industry seems trivial with their rather stereotypical processes and analog techniques, when compared to the pioneering power of the automotive or mechanical engineering industry. In addition, the industry is not really getting off the ground when it comes to digitization (Agarwal et al., 2016). Nevertheless, there has to be a major restructuring in the near future. This is mainly due to the existing building stock which is in high need of renovation and causing 79 Mton CO_2 emissions annually. This leads to a contribution of 40% of the total energy use and 36% of the CO_2 emissions in the European Union. To deal with the climate change, European climate and energy objectives were defined. By 2050, CO_2 emissions should be cut to 80-90% compared to 1990 and all buildings should be energy-neutral (European Commission, 2019, European Environment Agency, 2015).

Although there is enormous potential for optimization if digital technologies were used, the renovation industry applies mainly manual on-site renovation techniques, resulting in a low renovation pace, high labor costs and a long duration (Decorte et al., 2020, Lange and Krämer, 2019). This is especially questionable since the building industry is one of the key industries for the national economy, which employed around 2 million people and produced a construction volume of approximately €400 billion in Germany in 2018 (Federal Ministry of the Interior, Building and Community, 2020). This enabled a contribution of 5.3% to the overall economic gross value, which puts the building industry even ahead of most of the individual industrial sectors (Federal Ministry of Labour and Social Affairs, 2019).

Initial studies show that the integration of smart factories is also possible in the manufacturing process of renovation panels for old buildings (Decorte et al., 2020). The dovetailing of industry and construction would create new, more efficient manufacturing structures that can both comply with the required housing demand and reduce CO_2 emissions to a uniform standard to achieve the climate targets on time.

However, the introduction of novel technologies in new application areas may be challenging. The increasing demand in customized products is resulting in a higher complexity in production processes. Every day, several hundred houses have to be renovated, measured beforehand, and their renovation elements have to be produced with centimeter precision. In addition, unlike in the automotive industry, there are no fully identical buildings in the construction industry.

This paper explores how data from the buildings being renovated can be used to manage logistics processes, such as ordering, transportation, or storage, along the supply chain and aims to address this intention by designing the data supply chain of a smart factory to be developed in the construction industry. Accordingly, the research question of this study can be summarized as follows: How can building data be obtained, processed, and used to control logistics processes of a smart factory?

The outline of this paper is as follows. Section 2 presents the background of data supply chains, BIM, and smart construction factories by reviewing relevant literature. Section 3 describes the methodology which is applied in the development of the data supply chain of a smart construction factory in section 4. Lastly, section 5 summarizes the results, illustrates the recommendations for future research, and concludes the paper.

2 Background

In the following sections the theoretical background for this paper is discussed and relevant definitions are presented to reach a common understanding. This review of existing literature is organized as follows. First, we present the relevance of this paper by evaluating the systematic research. Second, we outline the function and structure of data supply chains. Third, we explain the purpose of BIM. Fourth, we emphasize the production and logistics processes of smart construction factories.

2.1 Literature Review

A systematic literature analysis according to Baker (2000) was performed to identify the development of smart factories and data supply chains in the building industry. The literature review was conducted using Scopus, Elsevier and EBSCO-host in May 2021 focusing on English and German literature from 2015 onwards. The following variety of keywords was used:

- (<Smart Factory> OR <Intelligente Fabrik>) AND
- (<Data Supply Chain> OR <Digital* Supply Chain> OR <Digital* Logistik*>) AND
- (<Building Industry> OR <Construction Industry > OR <Civil Engineering> OR <Bauwesen>)

Keyword category one focuses on the development of smart factories, category two on data supply chains and digital transformation of logistics, and category three on the building industry. The joint consideration of category one and two shows that there has been scant inclusion of logistics in the development of smart factories to date, as production is still the top priority. Categories one and three show that it will be possible in the future to manufacture entire house units in a decentralized manner in smart construction factories. However, a large number of the publications in these categories relate primarily to the structure of smart factories and not to the production of house units. The mention of digital supply chains together with construction has also been insufficiently explored.

The final combination of the categories shows that there has marginally been any cross-thematic work that represents the interdigitation of smart factories, the building sector/BIM, and data supply chains (see figure 1). The scientific relevance of this paper derives from this research gap, which is to be closed by the design of the data supply chain, in addition to the challenge of reducing CO_2 emissions and housing shortage.

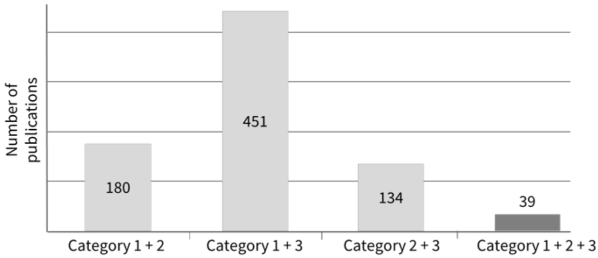

Figure 1: Number of relevant publications

2.2 Data Supply Chains

In Industry 4.0 digitization reaches a new level through a variety of innovative technologies, intelligent software tools and cloud-based communication. One of the most important trends is called "Digital Twin" which is a virtual representation of an engineered object or system that is updated from real-time data and thus spans its lifecycle by using simulation, machine learning and reasoning (Herlyn and Zadek, 2020, Wright and Davidson, 2020). The generated data has become the fifth new production factor after land, labor, capital and technology and created a digital economy (Wang and Huang, 2021).

In logistics, suppliers, manufacturers, customers and service providers use, generate and share digital information with each other that lead to a multitude of challenges and opportunities (Büyüközkan and Göçer, 2018). Current supply chains are in constant evolution which is driven by changes in the markets and emerging needs of the fourth industrial revolution era. For this reason, new terms for digitalized supply chains (DSC) have been flourishing combining the digital twin concept and logistics (Garay-Rondero et al., 2019). Kinnett (2015) describes a DSC as an intelligent, value driven network that leverages new approaches with technology and analytics to create innovative forms of business value, through a centric platform that captures the utilization of real-time information emerging from a variety of sources. Otherwise, Büyüközkan and Göçer (2018) define DSC as a system that is based on the capability of data disposal and communication for digital hardware, software, and networks to support and synchronize interaction between organizations.

In a DSC, the data supply chain describes a specific area of expertise that focuses on the reuse of existing data and that represents a lifecycle for data (Singh et al., 2021). The data supply chain begins when data is created, imported, or combined and then flows freely through the supply chain (Li et al., 2018). Unlike the traditional supply chain, in which products do not return to the original producer, the data supply chain is close-looped (see figure 2). It consists of three parts. On the supply side, data is created, captured, and collected. In the management phase, data is enriched, analyzed, and improved. On the demand side, data is used and exploited (Li et al., 2018).

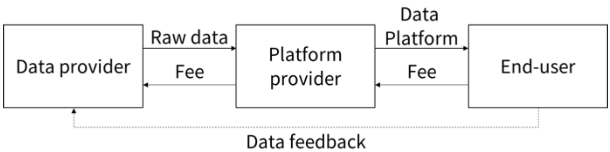

Figure 2: Closed-loop data supply chain model

In principle, a data supply chain works like a real-world supply chain, in which raw materials are transformed into finished goods. In the data supply chain, the unprocessed data represents the raw material that needs to be improved to create a product. It is about controlling the amount of data available along the information flow by putting it into standardized formats that can be read by the appropriate systems (Abandaa et al., 2017). The data is also stored in a warehouse, then processed and analyzed before being made available as a tangible product in the desired format. The companies that generate the raw data are often not yet in a position to analyze the data themselves or have the intention of selling the data. In both cases, the raw data is bought by platforms that measure and process the value of the data and then resell it to the users of the data (Li et al., 2018, Groth, 2013).

2.3 Building Information Models

In construction industry, data containing information about buildings has been largely generated and represented by BIM. BIM is a method that enables the networked planning, execution and management of buildings based on the continuous use of digital representation (Borrmann et al., 2018). The result represents a virtual three-dimensional model of a building, that contains the combination of graphical data, non-graphical data and documents related to a building or construction project all stored and managed together in a common software environment (see figure 3) (Erdélyi et al., 2021). It delineates a reliable basis for decision-making during the entire life cycle of the building, from conception to deconstruction (Ibrahim et al., 2019).

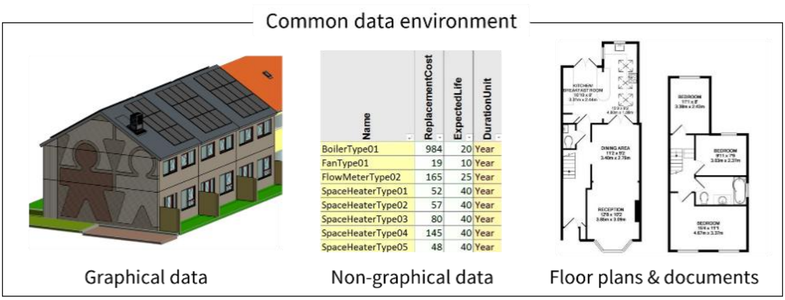

Figure 3: BIM model components

Each building component is to be described by a multitude of attributes. The model provides the historical development of all information through the construction stages (Pocobelli et al., 2018). In today's construction planning, an architect creates in the beginning a sketch with the help of Computer Aided Design (CAD) systems. The building then passes through various lifecycle phases, starting with requirements planning, followed by design, negotiation and tendering, construction, use, renovation, and demolition. In each phase, a large number of documents describing the building status are generated (Mehta et al., 2018). In addition, quantity takeoff is generated to determine costs. This requires linking the geometries with qualitatively and monetarily defined service components so that the individual quantity details can be summed up in service items (Monteiro and Martins, 2013).

BIM models improve the information flow between stakeholders involved at all stages of the supply chain, since data is collected centrally in one place. This is resulting in an increase in efficiency by reducing the laborious manual re-entering of information (Borrmann et al., 2018). However, a BIM model still does not represent a digital twin, as it is not designed for real-time operational response (Pan and Zhang, 2021).

In the future, BIM models will be applied even more to existing building needs, so that not only new buildings are digitally mapped. One of the essential technologies that can make this possible is scan-to-BIM. In a scan-to-BIM-process, a laser scanner is used to capture an accurate 3D scan of the real-world conditions (Rausch et al., 2021, Bosché et al., 2015). The output from scanning is similar to the data obtained from photogrammetric surveys and includes high resolution images, point clouds with triangulated and textured surface models. The main advantages of the laser scanning technologies are characterized by high geometric accuracy and fast measurements (one million points per second) in comparison to traditional optical and satellite geodetic methods (Badenko et al., 2019).

Since the technology is mainly used to measure existing buildings, it can consequently be used for the preliminary work of a detailed energetic renovation. Thus, the houses with high CO_2 emissions can now be scanned in order to produce customized renovation packages, consisting of facade and roof panels, on the basis of the resulting scan-to-BIM models. With the assignment to the data supply chains of intelligent factories, the data can be directly integrated into the procurement, production, and distribution processes. This opens up new possibilities for driving forward the digitization of the construction industry and reducing CO_2 emissions to meet climate targets on-time. This is the main focus of this paper. Since the panels to be produced are manufactured offsite in so-called smart construction factories, it is important to introduce these for a fluent integration into the data supply chain to be developed.

2.4 Smart Construction Factories

The expectations for Industry 4.0 are clear: manufacturing companies want transparency, traceability and process optimizations to reduce repair as well as maintenance costs while increasing machine availability and efficiency (Bosch, 2021). In the future it will be possible to produce entire house units in a decentralized manner in smart construction factories that aim for a standardized, cost-effective and faster production of residential properties compared to conventional construction on-site processes (Tetik et al., 2019, Vestin et al., 2018).

By manufacturing according to an industrial scale, the housing shortage can be counteracted. Furthermore, these factories can target the market for old buildings and renovation projects as the production of customized renovation packages is also possible. These consist of prefabricated wall and roof panels, which can be additionally supplemented with solar panels or heating and ventilation systems (Zander et al., 2020). In this context, production planning has to consider how the processes of incoming goods, warehousing, production and outgoing goods can be controlled by cyber-physical systems (Yao et al., 2017).

Smart construction factories have diverse data sources. In particular, they obtain their production data from BIM models of houses being renovated. Based on the derived number of windows and doors and the square meterage of the facade, they can manufacture panels to the millimeter. Furthermore, the factory, as the center of the supply chain, continues to have all necessary data of procurement and distribution. Based on part lists it knows at what time which materials arrive at the factory, to which panels they belong and when production has to take place in order to transport the panels to the construction sites on-time (Rausch et al, 2021). A challenge in developing the data supply chain is to convert any existing data into a uniform format for production and logistics control.

3 Research Methodology

The data supply chain is an essential part of the digital supply chain. Thus, it can be developed using the "Digital Twin Concept" (DTC) by Grieves and Vickers, which is based on the idea that a digital informational construct about a physical system could be designed as an own entity. By using the concept, a twin of the information is created that is embedded within the physical system itself and which is now linked with the system through the entire lifecycle (Grieves and Vickers, 2017). The DTC contains three main parts:

- Physical products in real space,
- Virtual products in virtual space, and
- Connections of data and information that ties the virtual and real products together.

On the one hand, the DTC identifies, how the digital twin can move from a concept to a critical component of an enterprise-wide closed-loop product lifecycle. On the other hand, it shows how the connection between the data about the physical product and the information contained on the virtual product has to be synchronized to use this information for a digital factory simulation. The DTC is based on three principals to solve innovative problems at any time with the same scheme (Grieves, 2014):

- Conceptualize visually the manufacturing processes.
- Compare the formation of the physical product to the virtual product in order to make sure that the product produced is as imagined.
- Collaborate with others throughout the supply chain to have up-to-the-minute knowledge of the products.

In the beginning of the development of the digital twin, a fully annotated 3D model of the product is designed. In the second step, to be able to simulate the production processes digitally, the needed manufacturing processes including the Bill of Processes (BOP) and the Manufacturing Bill of Materials (MBOM) are engineered. This simultaneous view and comparison of the physical and virtual product can acquire major benefits, especially in the real-world manufacturing phase of the product. Lastly, a Unified Repository (UR) tool is needed that is delivering the substantial benefits from the linkage between virtual and physical products (Grieves, 2014).

4 Development of the Data Supply Chain of a Smart Construction Factory

The conceptual development of the data supply chain is structured as follows. In the analysis, the linear supply chain in which the data is transferred is discussed to gain a basic understanding of the building industry. Based on this, the physical products in real space and virtual products in virtual space are identified. Further, the smart manufacturing system requirements are analyzed to check which properties the digital twins have to possess. In the development phase, the data supply chain for a smart construction factory is designed. Finally, a system is presented that acts as an UR tool and can control the data of both the virtual and physical products.

4.1 Analysis

The main supply chain processes in which the necessary data is produced, used and transferred is presented in figure 4. At the beginning, the operating company of the smart factory receives the order for the renovation of a building, which is then measured with 3D scan systems. As a result of the scan-to-BIM process, a virtual image of the building is created. Based on this, an architect designs the renovation packages. The data of these packages are converted into the machine language of the simulation systems and production machines.

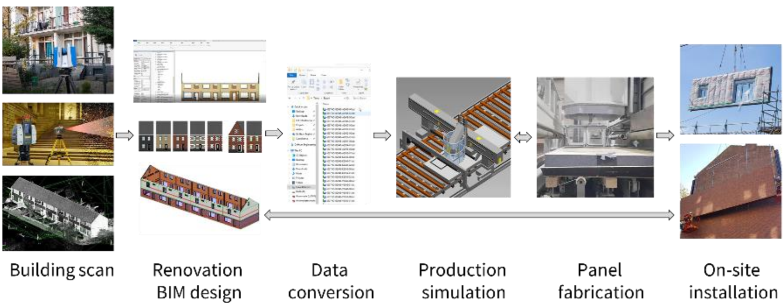

Figure 4: Process Overview

The virtual simulation of the automated production process is done on basis of this data. Afterwards, the panels are physically produced and then again compared with the virtual images to make sure that the product produced is as imagined. In a next step, the panels are transported to the construction sites and installed. Finally, the refurbishment packages are connected to the house monitoring system in order to obtain a daily status of the life cycle. This can in turn be linked to the BIM model, which would also create a kind of closed-loop process here.

Following the process illustration in figure 4, it is necessary to define the system requirements of the digital twins to ensure smooth integration. In the data supply chain to be developed, the digital twins can basically be divided into “product” and “production”, which need to be put into relation. The relationships between both twins can be represented in form of a Venn diagram to graphically organize the association between the requirements and components (see figure 5). It can be used to highlight where the digital twin product and the digital twin production differ and where they have commonalities, or which data is identical and how it is related.

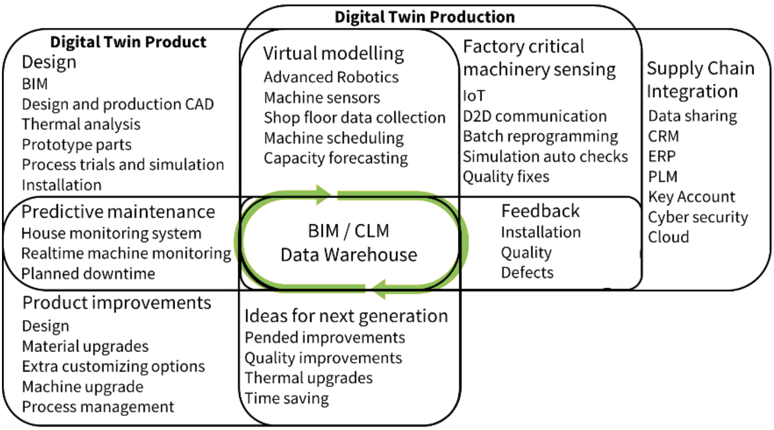

Figure 5: Smart Manufacturing System Requirements

For the product, a good basis is already available at the beginning. With the BIM model of the house to be renovated, the digital product is available virtually immediately after the scan-to-BIM process. However, in order to create a digital twin from the BIM model, further measures must be carried out.

After the prototypical BIM model of the product has been created, the relationships between the components are defined in the design intent as part of the product development, and a thermal analysis is carried out in order to check whether the CO_2 emissions of the houses can be reduced. Next, the life cycle of the products is analyzed and the first factory blueprint is designed. During the launch of the product, the production and logistics processes are developed, and the CAD relationships of the machines are checked. Subsequently, the processes can be presented in a trial. Finally, the products are manufactured for the first time in a test environment. As soon as error-free production is possible, customized products are designed, produced and later installed on the construction sites.

In the digital twin of production, which represents the smart factory, the components are virtually modelled. Corresponding data of the processes have to be collected in order to generate a twin of the production, which represents a real-time representation of the physical processes. This is supported by factory critical machinery sensing, which integrates Industry 4.0 technologies into production. The feedback from other processes in the supply chain is important in order to be able to adapt the processes accordingly and to collect ideas for the next generations.

In order to obtain a real-time operational response for both twins, predictive maintenance has to be considered to detect errors at an early stage (Çınar et al., 2020). For the products, this is mainly possible through the house monitoring systems.

Furthermore, supply chain integration plays an overriding role, as it involves all stakeholders (Ivanov and Dolgui, 2021). In particular, uniform communication channels for data exchange, respective customer relationship management (CRM) and enterprise resource planning (ERP) systems as well as key account management must be considered here. In the future, these processes could be controlled by configuration lifecycle management (CLM) systems, which are explained in the following chapter.

4.2 Development

The development phase refers to how the available data in the supply chain can be transferred into uniform formats in order to control the respective processes and tie the virtual and real products together. The developed concept of a data supply chain of a smart construction factory is presented in figure 6.

After the 3D measurement of the buildings, the data of the point cloud models are converted to BIM models using Revit, a BIM software that brings all architecture, engineering, and construction disciplines into a unified modeling environment (Autodesk, 2021). The BIM models are usually in Industry Foundation Classes (IFC) format. In addition, an OBJ file is exported for later simulation and production. Both files are sent to the warehouse of the data supply chain, where they are processed. The warehouse consists of the Autodesk BIM software, the manufacturing CAD server and the CLM system. Autodesk BIM is responsible for all actions related to the design of the building. The CLM system organizes the procurement, logistics and transports and takes care of customer management. The manufacturing CAD server controls the production. SQL servers as data migration tools coordinate the transfer between the individual areas.

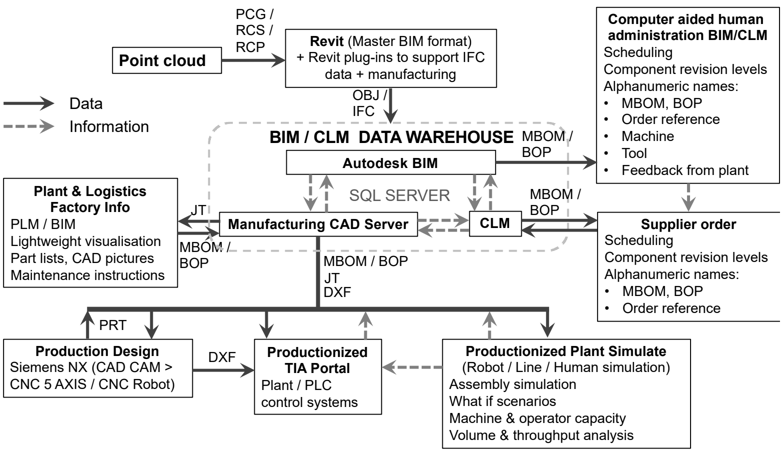

Figure 6: Data Supply Chain of a Smart Construction Factory

The first part of the warehouse is the Autodesk BIM software, that, in addition to design and building management, can be used to define the required MBOM, in which all details such as item numbers, quantities, part descriptions, and lifecycle state are listed that are needed for production. Through exchange with the manufacturing CAD server, the BOP can be created. Both files are then used within the computer aided human administration portal to create the corresponding orders for the factory, to forward them to the accounting department and to create production sequences.

The CLM system as second component of the warehouse is responsible for the contract management from initiation through execution, performance and renewal/expiry and covers all functions of ERP, PLM and CRM along the product life cycle. Thus, all procurement, warehousing and transport processes are coordinated and contracts are agreed with the relevant companies and service providers.

The third part is represented by the manufacturing CAD server, which converts the BIM models and their MBOM and BOP into the corresponding JT and CAD files, sends it to the production, and thus assigns the materials to the specific panels. Before this, the corresponding simulations is carried out. In this case, Siemens Tecnomatix Plant Simulation was selected visualizing the physical twin in real-time. Since this allows the integration of a physical system with the virtual environment, it is able to retrieve data of events from the physical twin via the cloud-based database (Siemens, 2020) Here, the various parts of the physical twin that function and move together are grouped (Redelinghuys et al., 2020). After the processes have passed the plant simulation, they are forwarded to the Totally Integrated Automation (TIA) portal, which provides complete access to the entire digitized automation from digital planning to integrated engineering to transparent operation and establishes the direct link to operations. If even more accurate product models are needed, they could be created beforehand in Siemens' NX interactive CAD system.

A closer look reveals that the data supply chain is not a linear chain, but rather an adaptive network, which enables connectivity, transparency, resource optimization, and faster response times (Singh et al., 2021). Thus, the normative planning area as well as the operational machine area are now decoupled from the physical material flow and decisions are made decentrally on basis of the available real-time information (Tao et al., 2019). The resulting supply chain network is thus an integrated set of digital logistics functions driven by a connected information flow (Sinha et al., 2021).

The greatest insight gained through the conceptual development of the data supply chain is that a link between the players in the building industry and in particular between old buildings and smart factories can be created. Within a few days after being measured, buildings can be renovated in a climate-neutral way. Decentralized production is many times faster than traditional manual renovation on site. Communication with suppliers, service providers and customers is largely digital and based on previously defined contracts. Furthermore, production is resiliently linked to the construction sites, which means that there are no nonconforming products in the event of short-term errors, as the system can react quickly. In the end, the data supply chain shows how the DTC from Grieves and Vickers works in practice and how it can be used and how digital twins can move from a concept to a critical component of an enterprise-wide closed-loop lifecycle. On the other hand, it shows how the connection between the data about the physical product and the information contained on the virtual product has to be synchronized to use this information for a digital factory simulation.

5 Conclusion

The paper shows how production processes in the building industry are changing through the integration of smart construction factories. In this context, a conceptual data supply chain was developed following the approach of Grieves and Vickers. The data supply chain is based on two digital twins, product and production, and is controlled by a digital core, the data warehouse, which consists of Autodesk BIM, a manufacturing CAD and a CLM system. As a result, an adaptive logistics and production network is created. Consequently, any processes in the supply chain are likely to be transparently coordinated with each other. Finally, this can make a significant contribution to climate protection and housing shortage, as manual on-site construction processes can be replaced by efficient decentralized mass production.

The most valuable constituents in the data supply chain from a logistical and manufacturing viewpoint are algorithmic and parametric designs for describing the geometry of all individual parts making up the full renovation package MBOM to be used by suitable software able to automate the planning of key process operations.

However, it is to be mentioned that this investigation was predominantly based on the combination of Autodesk Revit as well as Siemens Tecnomatix Plant Simulation and thus only one possible solution was tested. The software used is a studied example of how the conversion of data with subsequent production of products can work. Of course, other systems from different manufacturers can also be used.

The restriction of the investigation represents the few researches about the interaction of smart factories and the building industry. Furthermore, there are no fully developed CLM systems that ensure safe application and integration into the chosen simulation software. For future research, we propose that the transfer of BIM models into real CLM systems of existing enterprises is to be investigated. Nevertheless, the construction companies and housing cooperation are now being forced to push themselves ahead with digitization in their industry in order to meet the specified guidelines on-time.

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