Integration concept of Digital Shadows and BIM for a long-term optimal decision support in factory planning

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Abstract

Industrial objects nowadays rapidly transform due to the development of digital technologies. The concept of the *Factory of the Future* (FoF) involves digitization of all parts of the factory. In this paper two technologies are motivated and considered as the basic technologies that should be used in FoF: *Digital Shadow* (DS) and *Building Information Modelling* (BIM). Basic theory on these issues is given and potentials of BIM and DS integration is formulated. Based on the ability of digital technologies, their integration and convergence to generate value, definition *Digital Asset* is introduced from the economic point of view as a digital resource which brings economic benefit. A concept of integrating BIM and DS technologies for decision support in factory planning is formulated, including Life Cycle Assessment (LCA) and semantic modeling. The concept includes a description of the aggregate of technologies and their interconnections as a Digital Asset of the FoF. Further research objectives are focused on integration of BIM and DS which requires their interoperability ensured by an Ontology-Based Data Access (OBDA) approach, based on the Semantic web.

1. Introduction

All over the world, manufacturing systems have to deal with the challenge of fast-changing market conditions and rapidly increasing global competition. Fast-reacting adaption of production systems to constantly changing external and internal conditions is required, which results in a high production process and factory planning complexity [1–3]. In particular, a close interconnection and a constant data exchange between these both engineering domains is crucial for sustainable factories and production process planning decisions. Normally, several technologies or engineering domains are used in the same industrial objects but not all of them are connected in one digital entity. In this case management of industrial objects faces “information silos” which means that domain data and information interconnections, which are present in physical world, are not always digitized and normalized in digital representations of the object.

Therefore, it is necessary to integrate BIM and DS technologies to enable sustainable, long-term factory planning decisions, based on the LCA. A comprehensive methodology of the integration has to be elaborated, defining and evaluating its added value by the means of introduced Digital Assets. The fundamental problem of the integration is the interoperability of specific DS with specific BIM models, based on a matrix of requirements and constraints. For the operative part of the integration, semantic interoperability between BIM and DS domains has to be examined. With an ontology-based approach, a new level of cross-domain collaboration and knowledge generation is proposed in this paper. Furthermore, transfer possibilities and generated values of dynamic LCA data, generated from the BIM and DS integration, into static factory planning processes are examined. As a result, a coherent method for efficient and direct decision support for holistic life cycle optimization of factories, based on BIM, DS and LCA, is proposed in this paper.

In order to analyze and conceptualize this issue the paper is organized in the following structure. First of all, theoretical basics are given for the Factories of the Future, BIM and DS in particular. Second, the added value of technologies' integration is analyzed and consequently conceptualized in the term of a Digital Asset. This issue is followed by an analysis of the Semantic web as an integration technology, in particular by the means of the Ontology-Based Data Access (OBDA). Based on the issues mentioned above, factory planning and decision making using the LCA approach are described. Finally, all of the sub-components are integrated in a holistic concept of a Factory of the Future and form a Digital Asset structure of the factory.

2. Theoretical Basics

2.1 Factory of the Future

Particularly in today's global markets, constant changes in requirements are inevitable, therefore, modern factory planning must react with sustainable and long-term concepts. This in turn, increases the requirements in the planning process [4]. The development of technologies in the area of Industry 4.0 has led to the emergence of the concept of a digital FoF as a system of integrated technological solutions that provide the shortest time to design and manufacturers globally competitive next-generation products. It is defined as a system of integrated engineering domains such as production infrastructure, production processes and the product [2]. In the FoF, the Digital Shadow technology refers to the production process and the product, while Building Information Modelling provides digitalization of the production infrastructure [5, 6]. The FoF supports the entire production lifecycle from the development and planning stage and ends with the creation of a Digital Shadow [4], a BIM model and the concept of a smart and virtual factory [7]. Thereby the virtual factory stands for the digital representation of a real production site and a smart factory describes a self-organizing production environment. According to current studies [1, 2], the digital Factory of the Future is a promising concept for the decision support in factory planning.

2.1.1 Potentials of the integration of BIM and DS

BIM models contain detailed information about three-dimensional geometry of the FoF facilities, the appropriate rich semantics of structure elements and all engineering networks in buildings, as well as detailed information on the function of the infrastructure supporting the production process [8]. The Digital Shadow represents the entire production of the FoF and its processes, including its products and peripherals [4, 7]. The scientific community predicts cross-sectorally that the integration of BIM and DS technologies are inevitable for the future-oriented development of the FoF. According to [1, 10], these technologies are intended for the digital representation of different objects but simultaneously related to parts of the same physical asset. Nevertheless, they are developed in parallel and often without interconnection, despite a close physical connection between both domains [5, 12]. Currently, the digital technologies of BIM and DS are hardly even associated in terms of the FoF, caused by the fact that their data is very heterogeneous. At present, the lack of an adequate concept of integration of DS technology with BIM technologies significantly slows down the progress in research and development for digital, smart and virtual factories. Thus, developing a valid concept for integrating said technologies creates enormous added value in the planning and management of factories across industries.

The advantages of digitalization of the entire production environment refer to the entire life cycle of factories and their products equally, since essential long-term decisions and adjustments can be made with higher planning quality and reliability based on the data obtained from the Digital Shadow and the BIM of the FoF (e.g. the optimization of the trajectories of transportation vehicles and workers [9]).

Therefore, the issue regarding the role and place of the concept of the FoF in the formation of production assets is actively discussed by the scientific community and businesses, but it has not yet been sufficiently developed. Furthermore, the method of the Life Cycle Assessment based on these technologies can make planning even more sustainable by simplifying or anticipating quick adaptations to changing conditions through long-term oriented planning. Based on the existing potentials and the insights that can be generated, the result of the combination and convergence of BIM and DS technologies can be considered as a *Digital Asset* of a company, providing economic benefits (see Chap. 2.1.2).

The imbalance between the high demand for collaborative and holistic conception for the integration of BIM and DS technologies on the one hand and one-sided solution approaches on the other hand shows the urgency to investigate different possibilities for the integration of the two mentioned technologies. Related to this is the need to develop appropriate principles and methods and to evaluate the effectiveness of the imbedding of these technologies in the context of the FoF. This is precisely where this contribution comes in. It is also urgent to identify the potential of the FoF in an actual case. Therefore, in order to realize Factory of the Future technologies, the following features are required:

- adequate digital representation of physical construction objects;
- adequate digital representation of physical production items;
- bidirectional data flow between physical and digital world;
- ability to be integrated into the factory Product Lifecycle Management (PLM) system;
- ability to be used in factory Life Cycle Assessment (LCA);
- ability to generate value and reduction of operational expenditures.

BIM and DS technologies have such features and therefore should be the core technologies in the Factory of the Future and have to be integrated in order to accumulate convergence between applied techologies.

2.1.2 Added value of the integration: The idea of Digital Assets

According to economic theory, an asset is any resource owned or controlled by a business or an economic entity. This is anything (tangible or intangible) that can be utilized to produce value and that is held by an economic entity and that could produce positive economic value [13]. Therefore, we use the term *Digital Asset* in order to describe a digital entity (resource) which belongs (or partly belongs) to the owner and can potentially generate economic value. BIM, DS and their convergence [14] are actual examples of Digital Assets due to the fact that they are able to reduce operational costs [15–16].

Minimization of time and errors during changeover of production factors, which provide the main advantages of the proposed approach, must be taken into account when developing and operating the FoF. In our opinion, the management of factors should be ensured through the integration of BIM and DS technologies, synchronized in data transfer formats and in time. Integration of BIM and DS technologies within the framework of a single information model FoF will allow to combine all the knowledge and competencies that are formed through the entire life cycle: design, creation, validation and operation. Thus, the FoF information model becomes a Digital Asset that unites the knowledge base about an object. The Digital Asset, on the one hand, must have integrity, which means to be an adequate representation of a single physical object - FoF. On the other hand, the Digital Asset must have divisibility, which means that it must satisfy the requirement of sharing information between participants in the life cycle of an object. Integration of BIM and DS is a prerequisite for digital activation of the FoF in the form of an information model as a knowledge base accumulated by designers, builders and technologists. The integrity of such faculties implies constant synchronization of information about the actual parameters of FoF objects with their digital representations, as a result of which digital models are trained and the technical parameters of FoF are predicted throughout their life cycle.Without a doubt, the value of a Digital Asset can be obtained through the separate implementation of BIM and DS technologies. In addition to this fact, their integration is multiplicative, which means that the holistic integration of these technologies also provides additional value for FoF. This happens due to the fact that according to the degree of their consistency that determines how quickly and with what precision in the organization, adjustments and operational processes will be eliminated. Due to the fact that digitization is a modern direction in science, there are no correct and widely spread methodologies to measure added value of digital items from an economic point of view. Therefore, a coherent methodology of estimating the value of the FoF as a Digital Asset needs to be developed.

Overall, we can consider the FoF model as a virtual asset with some value advantages. The estimation of this value is not trivial; it includes the estimation of both the values of BIM and DS and the added value of their integration. The Digital Asset has to be developed as a tool for this estimation to verify the costs of digital modeling and connecting domains.

2.2 Semantic Web as integration technology

Knowledge-based approaches have generally proved to be particularly suitable for modelling of complex production networks. They support explicit representation of knowledge in a relevant domain and the development of this knowledge through reasoning mechanisms, in order to provide effective services for cross-domain collaboration [17]. Semantic Web [18] extends the principles of knowledge-based approaches to scenarios on the Web by focusing methods for data integration and intelligent reasoning with large data amounts [19, 20]. The conceptualisation of the Semantic Web is enabled by ontologies, which are used for the definition of data semantics in a machine-readable way. Ontologies represent a set of domain data concepts, its taxonomy, interrelations, and the rules that govern such concepts [21, 22].

In the field of production engineering, the Semantic Web has received great attention for its ability to make interactions within Digital Shadows more flexible and automated. Several upper ontologies for manufacturing, such as DOLCE [23], SUMO [24] or MASON [25] were developed. Moreover, Semantic Web technologies have also been discussed in several research projects in infrastructure and building science. [26] presents a semantic reasoning framework for the integration of BIM data sources, which allow to detect errors of included 3D models. In [27], querying different BIM sources by using linked building data of different ontologies has been realized successfully. Despite promising results of using ontologies for semantic interoperability in both domains, the possibility of their connection has still not got proper attention. Open data formats, such as the Industry Foundation Classes (IFC) specification, have been developed to describe and exchange information within the architecture, engineering and construction industry [28]. However, the lack of semantic information hinders their application. In industry, initiatives such as the Open Services for Lifecycle Collaboration (OSLC) [29] try to establish the application of ontologies in engineering tools. Nevertheless, a comprehensive methodology of connecting BIM and DS domains based on Semantic Web technologies has not been developed yet.

2.2.1 Ontology-based Data Access (OBDA)

The main idea of the Ontology-Based Data Access (OBDA) approach is to use ontologies as high-level schema for governing multiple sources of diverse data, allowing users to directly access data via all-accessible RDF-Format. The access is enabled by a three-level architecture, consisting of the ontology, the mapping and the data source layers. An OBDA system translates user queries from a familiar vocabulary of the ontology into the vocabulary of the underlying data sources and then delegates the actual query evaluation to a suitable query answering system of the data source [30].

In the Cluster of Excellence ”Internet of Production” of the RWTH Aachen University, ontologies are supposed to be an enabler for a new level of cross-domain collaboration along the entire value chain of production technology [31]. Application examples reach from an implementation of the OBDA approach in laser processing, up to the creation of a cross-disciplinary catalogue with an overview of the data generated in the project [32]. Moreover, the OBDA approach has been approved to have a high potential for applications, in which data sources are multiple, diverse and not organized in a uniform and coherent way [32–34]. The concept of BIM and DS integration meets these application criteria. These technologies are very heterogeneous and include data ranging from 3D modeling of assets up to machine data streams from the shopfloor. With the OBDA-approach, an integration and management of the BIM and DS domains can be achieved.

2.3 Decision support in factory planning

Decision support in factory planning currently bases on static data only and requirements, neglecting dynamic process data of DS and the life cycle assessment (LCA) of the factory. As a result, only a short planning horizon of factory planning projects is possible, covering a small interval of the entire factory lifecycle. However, in today’s turbulent and volatile market it is no longer sufficient to limit the planning and design process of dynamic and highly complex factories to short-term periods of time. Rather, the long-term perspective must be taken into account already in the early phases of factory planning.

2.3.1 LCA

Life Cycle Assessment, also called Life Cycle Analysis, is a method originally used to evaluate the environmental impact of a product over its life cycle. It includes the extraction and processing of raw materials, manufacturing, distribution, use, recycling, and final disposal [35]. At each level of the life cycle, all energy and material flows exchanged with the natural environment are identified to examine the impacts in ecological impact categories. Thus LCA can also be used as an ecological assessment method for the effects of production processes, infrastructure and resources of a factory over its entire life cycle.

Although the life cycle analysis is ISO-standardized and established in many industry areas, it is currently used as an evaluation tool for existing products and production processes only. While various other software and tools of the FoF are already fully utilized in factory planning, LCA is currently rarely used and if so, it is not integrated into the planning process [36]. The reason for this lies in the high complexity of the currently used databases as well as in the lack of knowledge regarding suitable interfaces for integrating the LCA data into the planning process. This causes a major research gap, since the methodology could be further developed from a pure evaluation tool to a design tool for sustainable factories. Especially since the potential of LCA is already apparent in the context of factory planning and only needs to be utilized for this area of application.

It is a fact that in today's factory planning, decisions have to be made whose effects will last for many years. However, increasing dynamics and volatility in the environment of manufacturing companies, considering the longest possible period of time representing a major difficulty for the early planning phases of factories, as various variables and needs for long-term adjustments are still unclear up to this point. However, only the interaction of LCA, BIM and DS technologies is able to make reliable predictions about possible scenarios and their impacts during the life cycle of a factory. For this purpose, the LCA method requires an enormous amount of highly detailed digital data, which can be provided in the required quality and reliability by integrating BIM and DS technologies. In this context, the compatibility of the three technologies must be clarified.

2.4 Problem summary

The Factory of the Future needs to be based on the integration of DS and BIM. This integration is a basic requirement, as factory planning addresses the factory building and the design of factory equipment. The problem is that only when both planning areas are considered in an integrated manner, a meaningful, complete data source can be generated and an overall optimum of planning be achieved. Therefore, the data and planning-related integration of BIM and Digital Shadows need to be performed in terms of the FoF. This requires the development of an appropriate methodology that solves the fundamental problem of creating interoperability between project-specific DS and BIM models and the respective planning processes based on a matrix of requirements and constraints. The methodology must include a classification for the information models of BIM and DS in order to be able to define the requirements for the objects to be integrated. In addition, to achieve this goal, it is necessary to conceptualize the term Digital Asset and consider the evaluation of the added value of the integration of BIM and DS.

Moreover, the integration of DS and BIM technologies in the Factory of the Future requires a new level of cross-domain collaboration along the entire factory lifecycle. For this purpose, semantically adequate and context-aware data needs to be made available on an appropriate level of granularity, so that production engineering and planning models can be integrated into data driven optimization processes [37]. An integration network must span diverse domains of construction and production engineering models. Moreover, comprehensive networking of human and non-human production systems is crucial. Therefore, the integration network must be modular with respect to languages and tools and must make process information accessible and readable for all process entities, regardless of their origin and domain.

3. Integration Concept

In order to make the generated data, the Digital Assets, usable, an integration framework for BIM and DS has to be developed using the means of the Semantic Web. For this purpose, a possible integration concept has been developed, shown in Fig. 1.

Concept implementation is based on several steps of three different development directions, such as conceptualisation of Digital Assets, realisation of an ontology-based integration framework and application of LCA algorithms to the resulting network. First, a method of estimating the value of a factory as a Digital Asset needs to be developed. This step includes a development of a core set of Digital Asset characteristics. In parallel, the interfaces between LCA and factory planning methods need to be identified, including the estimation of the added value of LCA integration into factory planning. It is important to find out, which requirements arise from the additional information of BIM and DS and in which form they must be provided to the LCA. Based on the factory planning map, it should be determined at which logical points along the planning process planning information will change, if dynamic data from life cycle analysis (LCA) is used instead of the traditional static data. Furthermore, the interfaces of a dynamic correlation between BIM and DS need to be defined clearly, so that they can be integrated into a coherent network. After defining the theoretical basis of the integration framework, the connectivity of real production assets such as machine tools and building needs to be ensured. A consistent data infrastructure has to be established, so that the data of the real assets can fill their digital representations in a proper granularity. Based on the results of this step, a general methodology of a context-aware integration of BIM and DS digital models needs to be defined and implemented. Figure 1: Integration concept of Digital Shadows and BIM technologies

For this, the OBDA approach has to be used, enabling the querying and governing of distributed BIM and DS data sources. A three-level architecture, consisting of a high-level ontology, the mapping and the data source layers must be designed. The main challenge is thereby the conceptualisation of original domain data models with a proper high-level ontology, which allows a reasonable linking between the resources.

Moreover, the design of a mapping layer might also be challenging. This layer has to be able to translate user queries from a familiar vocabulary of the ontology into the vocabulary of the BIM and DS models and delegate the actual query evaluation to a suitable query answering system of the data source. Therefore, the mapping has to be designed modular with respect to the participating languages of all domains of interest. In parallel, a decision logic has to be designed to make the best decision based on the data from the LCA and the digital factory model. The core of the logic is the processing of the dynamic data from LCA and thus BIM-DS network into factory planning tools via proper interfaces. The final validation of the proposed solution can be anticipated through a Plug-In for a common factory planning tool, such as Autodesk NavisWorks or Inventor, by using the SPARQL endpoint of the OBDA system. Thereby, the integration of different dynamic data formats into static planning tools can be examined and the added value of the solution for decision support can be estimated.

To sum up, a method for efficient and direct decision support for the holistic life cycle optimization of factories can be designed based on the proposed concept. This central goal of the integration BIM and DS can be supported by the means of the Semantic Web. Factory-specific requirements can be used to maximize the overall optimum of factory design over the entire life cycle. To ensure this, high-quality data on all objects of the factory are required. This data can be obtained via BIM and Digital Shadows in conjunction with LCA, and has to be processed via an OBDA system. In doing so, LCA extends the existing data of the individual assets with future-related information, whereby valid future scenarios can be formed as a basis for planning. A bottom-up approach using digital factory assets ensures the availability of the required information in a seamless and up-to-date manner. The data of BIM and DS also helps to estimate the value of the connected solution by the means of the Digital Asset. In this way, a solid framework for the vision of the Factory of the Future can be delivered.

4. Conclusion And Outlook

In terms of a turbulent manufacturing environment, it is necessary to enable sustainable, long-term factory planning decisions, which can be done by integrating Building Information Modeling and Digital Shadow technologies, combined with a Life Cycle Analysis approach. LCA requires an enormous amount of digital data, which can be given by the integration of BIM and DS technologies. With the means of introduced Digitals Assets, the added value of the integration can be estimated.

However, until now, the digital technologies of BIM and DS are hardly connected, which is due to the heterogeneity of their data. Therefore, it was necessary to develop a comprehensive concept of a methodology of integration that defines and evaluates its added value based on the introduced digital assets. Furthermore, the integration of DS and BIM technologies requires a new level of cross-domain collaboration along the entire factory lifecycle. This requires providing semantically adequate and contextual data so that production engineering and planning models can be integrated into data-driven optimization processes.

The elaborated level of cross-domain collaboration can be achieved within the OBDA approach. For this, an ontology-based integration architecture needs to be designed, consisting of a high-level ontology, the data source layers of all domains of interest, and the mapping between them. The possibility of knowledge generation (reasoning) of ontologies can also support optimal decisions in the medium and long term.

In summary, it was possible to highlight that the integration of BIM and DS must serve as a basis for the use of LCA in order to make good and long-term decisions in factory planning. However, the integration of both technologies require their interoperability. This can be ensured by an Ontology-Based Data Access approach, centered around a Semantic web, which was presented in this paper.

The approach described is to be elaborated hereafter, substantiated by case studies and the results evaluated. Based on the validation results, the statement about the suitability of the OBDA approach as an integration technology in the FoF can be made. Moreover, the possibilities of new knowledge generation by ontology reasoning and the extendability of the whole network need to be further examined. Economic approaches to Digital Assets shall also be further developed, enabling an objective estimation of the costs and value of the domain integration in terms of the FoF.

Declarations

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Data availability

The paper has no associated data.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Consent to participate

The authors consent to participate.

Consent to publish

The authors consent to publish.

Competing interests

The authors declare that they have no competing interests.

Authors contributions

Factory of the Future concept was described by Vladimir Badenko, Nikolai Bolshakov and Aleksandra Mueller performed potentials of the integration of BIM and DS. Added value of the integration and idea of Digital Assets was introduced by Nikolai Bolshakov, Semantic Web as integration technology, ontology-based Data Access (OBDA) – by Florian Becker and Aleksandra Mueller, Aleksander Fedotov summarized decision support in factory planning. All the authors contributed to integration concept, described in the end of the paper.

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Figures

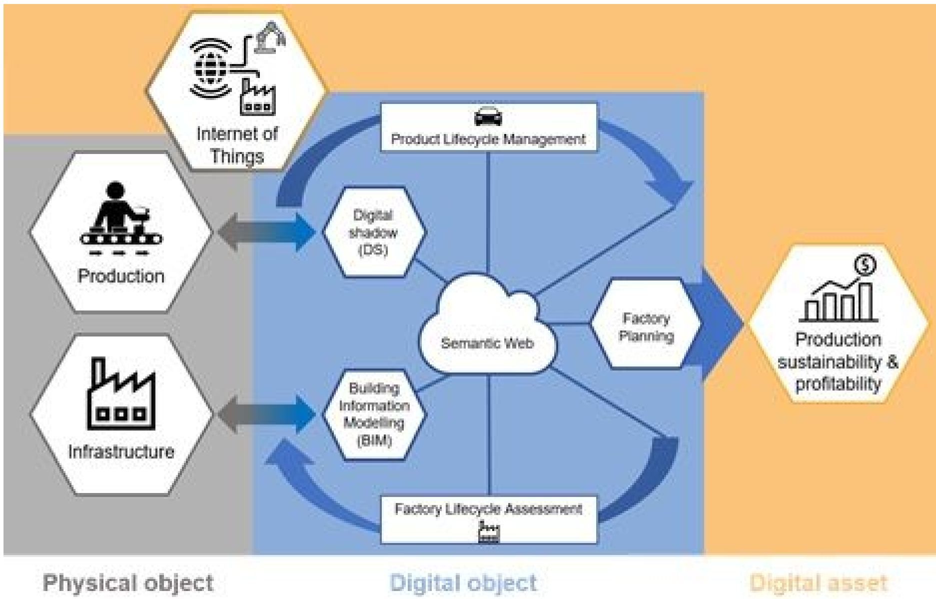

Figure 1

Integration concept of Digital Shadows and BIM technologies