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Integration of digital twin and BIM technologies within factories of the future

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Abstract. With the development of information technologies for industrial plants, more and more tools for digital design, creation and operation of industrial facilities are emerged. In particular, significant success in development of Building Information Modeling (BIM) and Digital Twin technologies (DT) should be noted, which act as tools for digital transformation and representation for construction and production technologies respectively. In this regard, in this article, the principles and methods of integrating BIM and DT technologies within the framework of the so-called “Factories of the Future” (FoF) are formulated. Wherein the physical twin of FoF includes both production technologies and production infrastructure with buildings, structures and systems included in it, while particular attention is given to Operation and Maintenances (O&M) stage of object lifecycle which is less developed in comparison with design and creation stages. In addition, this paper also considers the role of systems information modeling (SIM) in such objects. Moreover, the concept of “digital asset”, closely related to the FoF, is examined and semantically analyzed, especially from information ownership point of view. The features of convergence of BIM and DT technologies are analyzed, and the levels of development of these technologies are compared. Finally, the directions of further research in this interdisciplinary branch of researches and development are formulated.

1. Introduction

The Industrial Revolution, Industry 4.0, is determined by the comprehensive implementation of digital technologies and is associated with the urgent need to find an adequate answer to current challenges, which are caused by the need to ensure short timelines for the development of new products, individual product settings for the consumer (customization), and production flexibility, decentralization of management and effective cooperation, as well as resource savings [1–4]. The development of technology in Industry 4.0 has led to the emergence of the concept of a digital Factory of the Future (FoF) as a system of integrated technological solutions that provide the shortest time to design and manufacture globally competitive next-generation products. This system supports the entire production lifecycle from the research and planning stage, when the basic principles of the product are formulated, and ending with the creation of a Digital Mock-Up (DMU) [5], a Smart Digital Twin (SDT) [6], manufacture of a prototype or small series (“paperless production”, “everything digital”) and its further development – the concept of smart and virtual factories [7].

The concept of the FoF usually includes three elements with relevant information technologies: production infrastructure, technological equipment and the product, and the technology of digital twins (Digital Twin – DT) is thus decisive for indicating inclusion in Industry 4.0 [8, 9]. While DT technology refers to the product and technological equipment, Building Information Modelling (BIM) technology provides digitalization of the manufacturing infrastructure of high-tech industry, including buildings and facilities [10–13]. So, for example, in order to optimize the trajectories of the equipment and staff, during the planning and modeling of the FoF, it is necessary to use a navigation environment created on the basis of the actual (as-is) BIM model, which determines the parameters and restrictions of movement for people, as well as autonomous robots [14,

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15]. Consequently, BIM and DT technologies become key aspects in FoF especially in O&M stage of object lifecycle and LCC (lifecycle cost).

The necessity to establish a close relationship between the key information technologies of the FoF, first of all DT and BIM, is determined primarily by the fact that BIM models contain detailed information about three-dimensional geometry of the FoF facilities and the appropriate rich semantics of structure elements and all engineering networks in buildings where FoF are located, as well as detailed information on the functioning of the infrastructure supporting the production process, which is based on DT [13]. Therefore, the issue regarding the role and place of the concept of FoF, including DT and BIM technologies, in the formation of production assets, including digital assets, is actively discussed by the scientific community and business, but which, in our opinion, has not yet been sufficiently developed [16].

Digital technologies in industries, such as construction [17–19] and mechanical engineering [20–22], despite their close connection, developed in parallel and often without interconnection [23]. At present, in our opinion, the lack of an adequate concept of integration of DT technology with BIM technologies significantly slows down progress in research and development for digital, smart and virtual factories, production, etc. within Industry 4.0. Nevertheless, the scientific community predicts that the integration of BIM and DT technologies that are intended for digital representation of different objects, but which are related to parts of the same physical asset (and, as a result, digital asset) that make up the FoF, is inevitable [2, 4, 8, 10, 21, 22, 24]. Therefore, it is necessary to develop the basic principles of BIM and DT technologies integration, the absence of which impedes the development of digital technologies related to the FoF and does not provide effective coordination and unification of the relevant technical and economic aspects. Thus, we can formulate the thesis that the successful implementation of the concepts of Industry 4.0 as part of the development of advanced production technologies requires research and development in the field of integration of BIM and DT technologies based on the principles to be developed.

The practical implementation of DT technology is restrained by existence of a number of problems throughout the entire lifecycle of the corresponding production activity. Primarily these problems include lack of clear methodological foundations for determining the resulting technological and economic benefits of transformation based on DT, the difficulties in the technical implementation of DT technologies in different industries and various levels of reliability of the results obtained from different case studies of DT implementation [8, 6, 22–24]. At the same time, while there is a certain number of publications presenting research results on possible ways to solve the problems mentioned above [19–28], there are no publications which discuss problems related to the ownership of data and information in DT technologies, as well as integration between virtual objects described by DT technologies. These two problems are only mentioned but not analyzed in publications. Accordingly, the question of integrating DT with information technologies outside it, like BIM, remains unsolved and is also not considered in publications. Therefore, the study of the principles and methods of integrating DT and BIM technologies within the framework of the FoF concept, as well as assessing the economic and technological benefits of convergence of these technologies in the framework of introducing new production technologies, is an urgent task, which is considered in this article. One of the key provisions of digital twin technology is to provide bi-directional connection between a real physical object and a virtual object - its digital twin [9]. Therefore, when developing the principles of BIM and DT integration within the framework of the FoF, two-way information links between the production facility, technological equipment, engineering infrastructure and their virtual digital prototypes, including DT and BIM models, are investigated.

It should also be noted that when introducing BIM-technologies in industry, many problems are associated with the “digitalization” of existing objects, but not new ones, for which suit BIM models can theoretically be created, that initially take into account the future connection with the DTs of the manufactured product, technological equipment and production facility generally on exploitation stage of life cycle [29, 30]. The main technological difficulties in the “digitalization” of existing buildings and facilities are related to the need to reduce the complexity of obtaining initial reliable information for element recognition and filling the as-is BIM database, including the integration of attribute information in BIM, as well as post-processing often hidden and distorted structural and complex semantic information about the object [31]. Studies related to digitalization of asset management also show insufficient integration of BIM technologies and building management systems, including updating asset information and setting up bidirectional data exchange between a physical and virtual object [16, 32–34].

Thus, the objective of this article is to study the ways of integrating DT and BIM technologies, as well as developing appropriate principles and methods, assessing the effectiveness of the interpenetration of these technologies in the framework of FoF forming and solving the problems of introducing advanced production technologies. We emphasize once again that the interaction of DT and BIM technologies is further considered in the context of FoF, since they are objects that contain both production technology (DT) and appropriate production infrastructure (BIM). At the same time, the introduction of the integration of DT and BIM technologies at advanced production facilities will be the driver of FoF development.

2. Methods

2.1. Bridging gaps regarding effective integration of BIM and DT technologies

As already stated, the concept of the FoF is considered as systems of complex technological solutions that provide the shortest possible time for the design and production of globally competitive products of a new generation and implies the presence of three stages (technologies): digital factories, smart factories, virtual factories (Fig. 1) [35, 36]. Moreover, the success of the introduction of these technologies in the high-tech industry, in particular in the engineering industry, is associated primarily with the systematic use of DT technology in the framework of FoF [37–39].

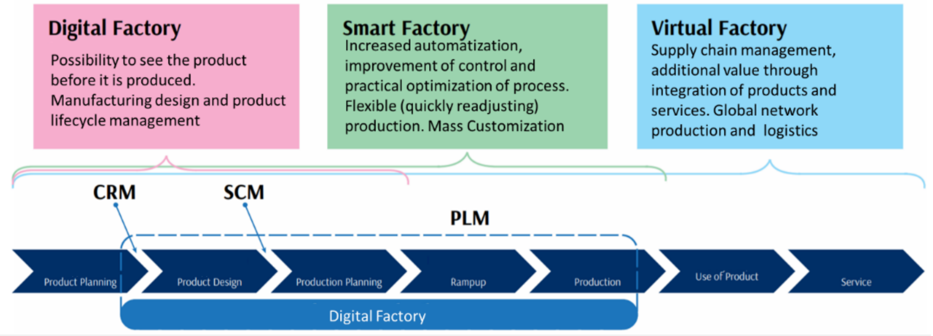

Figure 1. FoF: CRM – Customer Relationship Management; SCM – Supply Chain Management; PLM – Product Lifecycle Management [35].

It should be noted that in industrial and scientific sources, the definitions of DT differ in a certain variety [40–42]. In the framework of this work, we will use the following definition: DT is a digital representation of the behavior in various operating conditions of real physical objects – materials, products, systems, machines, structures, equipment, cyberphysical systems, including technological and production processes, etc. , which can only be described by a family of complex multidisciplinary mathematical models, including 3D non-stationary nonlinear partial differential equations with a high level of adequacy to real materials, objects, and physical and mechanical processes [37, 43]. Moreover, when we talk about products, we will use the concept of a “first level digital twin” (DT1), while in case of technological processes we will use definition “second level digital twin” (DT2). Integration of DT1 and DT2 in general refers to Smart Digital Twin (SDT) [37].

The definition of BIM technology, which is presented in the US standards, has a formulation similar to DT: building information modeling (BIM) is a digital representation of the physical and functional characteristics of an object; BIM is a common knowledge resource for obtaining information about an object, which serves as a reliable basis for decision-making throughout the entire lifecycle of an object, which is defined as existing from the earliest concept to demolition [44]. There are a fairly large number of publications that analyze the relationship between the two concepts – DT and BIM [45–49]. Like DT, BIM is a digital representation technology for real physical objects. In both definitions, a high adequacy of reality is noted, in the case of BIM this is incorporated in the reference to “a reliable basis for decision-making”. Both definitions focus not on the static representation of the object, but on its dynamic change over time in the context of the lifecycle. However, in the case of the DT, we are talking about a deeper study of the digitalization of the corresponding products and processes than in BIM.

Definition of the concept of the FoF [35] (Fig. 1) primarily focuses on the product and the technological processes of its production, without taking into account the fact that respective real factory is located within the framework of some production infrastructure that ensures its functioning [50, 51]. Moreover, in the framework of FoF on the part of the product a technology such as DT has already been developed to a large extent. Such approach is based on the definition and decomposition of the parameters and characteristics of the object being developed by DT technology, using the formation of the matrix of targets and resource constraints, including cost constraints, reaches tens of thousands of units [52]. A similar technology used in construction (BIM) is somewhat behind [16, 22, 53]. In our opinion, there are two reasons that further determine how to overcome the difficulties of integrating BIM and DT. Firstly, the dimensions of the construction object, buildings and structures are usually more significant than the objects in mechanical engineering, and the construction of each object is normally unique, only partially implying any kind of mass production. Secondly, until now, BIM technology has been intended to solve its own problems of construction and operation of a production facility – a building and engineering infrastructure, and did not pay due attention to interaction with technological equipment and, moreover, the product manufactured on it, which are “external” in relation to the BIM environment. Consequently, on the way to the development and creation of FoF, there is a necessity to integrate information modeling of buildings and structures (production infrastructure) into the digitalization technology of the entire production process, that is, first of all means to determine the ways and methods of integrating BIM and DT technologies. Thus, it can be stated that DT and BIM technologies can be integrated, as they are both digital and describe different elements of the same object – FoF.

2.2. *Integration of BIM and DT*

The requirements for the development of the FoF set the trend for new production technologies, and the adaptability of the factories to such new requirements using the integrated DT and BIM technologies will be their competitive advantage. The design, construction and operation of FoF should take into account the necessity in flexible and quick restructuring of production technologies, based on changes in consumer requirements. At the same time, as shown in Fig. 2, BIM and DT technologies are the basic elements of the FoF, while having both areas of contact (corresponding to the physical intersection of production and infrastructure, for example, at the level of supply of water or electricity), and their own elements, not affecting the other technology (for example, premises not used in production in BIM models or modeling of physical processes inside a DT of technological equipment that do not directly affect the external construction environment). We propose to consider DT and BIM technologies in conjunction, without perceiving the BIM technology as a service technology that lags behind the DT technology in terms of development [33], due to the fact that until now they have developed in parallel and solved problems from different spheres: construction and mechanical engineering.

An integral element of the FoF is also a management system, indicated in the Fig. 1 as SIM (System Information Modeling) technology. By SIM technology, we understand the support of the process of digital modeling of a complex connected system, which represents the general information resource, forming a reliable knowledge base [54].It is important to note that in this situation we use the concept of SIM but not concept of PLM systems (Product Lifecycle Management - product lifecycle management systems) which is close to it, since we assume that SIM includes transformation management systems for both products, technologies, and production infrastructure that are all the objects of management. We can say that SIM takes into account the transformation of PLM depending on changes in technology, adapting to these changes. The issue of including information management systems in the concept of FoF is beyond the scope of this article and requires a separate careful consideration, since, as mentioned above, the problem of ownership and management of information during the lifecycle of a DT object is one of the main obstacles to the development of digital twins. Within the FoF, we distinguish these three technologies that should work in close integration, not excluding the subsequent inclusion of others technology (Fig. 2).

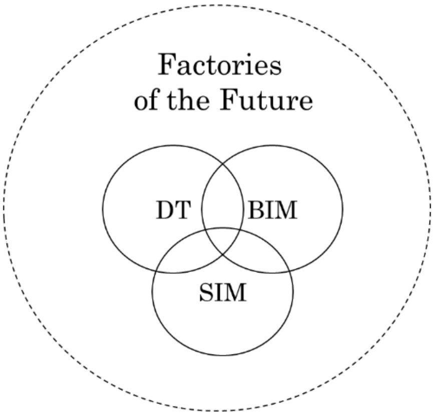

Figure 2. BIM, DT, and SIM technologies in FoF.

The methods for integrating BIM and DT technologies in the framework of FoF should be based on the following points presented below.

Currently, DT technologies are more developed in the sense of digitalization and creation of virtual prototypes of real objects, due to the fact that the objects that are represented by DT are products, which are more clearly defined and specific, for example, engineering products (engine parts, machine tools, etc.) or related technological processes (welding, casting, etc.).

Technological equipment should always be provided with engineering infrastructure, which is responsible for the operation of equipment during its entire lifecycle, including repair, maintenance and other types of work. At the same time, the management system for technological equipment and engineering infrastructure should be interconnected, and should be part of common management system of the FoF. The operation of such management systems should provide optimal operating conditions for both technological equipment and engineering infrastructure, in compliance with all safety requirements. To meet this requirement, it is necessary to model the joint work of all elements of the FoF: engineering infrastructure, technological equipment, products manufactured by the factory, and management system of the FoF.

Integration method of BIM and DT technologies in the framework of FoF should use one of the key and integral elements of existing DT technology which is a multi-level matrix of the targets and resource constraints (time, financial, technological, manufacturing, etc.) for the product as a whole, as well as for all components and details in separate [9, 55]. Such matrices usually are containing tens of thousands elements. Fig. 3 shows the process of forming such a matrix, which is formed for the FoF.

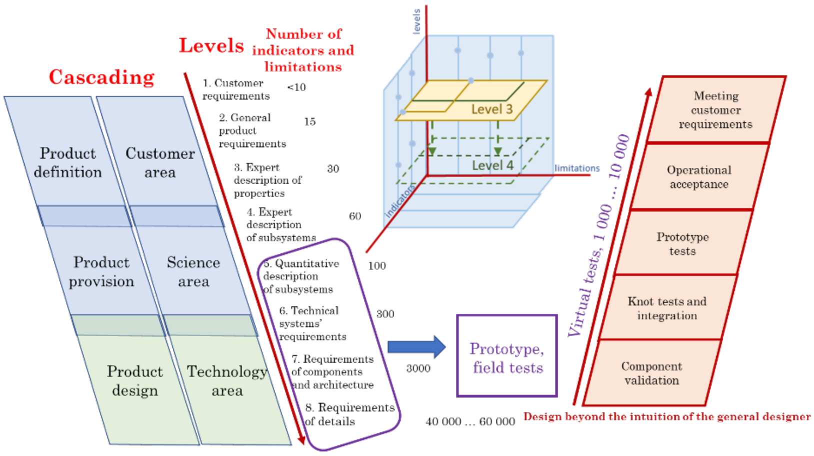

Figure 3. Formation of a matrix of target indicators and resource constraints [9].

The requirements of the upper level of the multi-level matrix of targets and resource constraints for the FoF (Fig. 2) are determined by the customer. These are restrictions on product quality, cost, safety, resource, finance, service, economic costs, and so on. Based on the requirements of the upper level, the next blocks are formed according to the type of tasks being solved. Based on all the data obtained for each block, an appropriate set of models of real objects and physical processes is created. At the same time, the validation of models based on field tests (with real objects) as well as the performance of tens of thousands of virtual tests for each component and the entire system as a whole are also an integral element in creating a highly adequate digital models. Due to its high adequacy, such a digital models allows to significantly approach the condition of real object to satisfy the requirements formed earlier in the constraint matrix (Fig. 3) – it provides a difference between the results of virtual tests and full-scale field tests within ± 5 %.

The same approach, although in more limited amounts, is used in BIM technology. Virtual tests are carried out at all levels of the object: material-element-construction-product [55–60]. Validation can be carried out both on the basis of cataloged data, and on the basis of tests of building materials and individual elements of buildings and structures and building parts – columns, lintels, etc. during the construction process. The transition to full-scale testing of the entire construction object, as it is discussed with most products developed using the DT technology (for example, cars and aircraft), is possible only with the start of operation of the construction object, and therefore the validation of the BIM model of the building or structure is postponed for the period of Operation and Maintenance (O&M). If we consider this situation, according to the theory of DT, based on the accumulated experience of the DT technology, it can be assumed that the driver of the development of BIM technologies for construction projects can be the accumulation of a field test database during construction and operation, the use of smart sensors and the intellectual processing and accumulation of this data, followed by the usage of their Digital Shadows (DS) and Big Data and for taking into account these refinements in the design, construction and operation of subsequent facilities.

It is important to note that, aimed at the digital representation of a real physical object, similar to DT technology, BIM technology focuses more on the work of users than on the object itself [61]. This remark is clearly demonstrated by the example of the analysis of information flows from the virtual world to the real world (virtual-to-physical) and from physical to real (physical-to-virtual), which are considered in detail by the founder of the concept of DT Greaves [62–64]. At the same time, if such a data flow is not organized than information model can be referred only as the Digital Model (DM), if the physical-to-virtual flow is automated than DM becomes a Digital Shadow (DS). If both flows are automated, then we can start talking about a Digital Twin with the full on-line bi-directional connection between virtual and physical objects. It means that DT is updated based on the readings of the sensors, to exactly match the real physical state of the object. It is sometimes noted that virtual-to-physical communications at the DT level are not given enough attention, although this is an important component on the basis of which a digital object can also act as a control element of a physical object, in other words, a change in the state of a physical object directly leads to a change in the state of the digital (virtual) object and vice versa [28]. For BIM, such flows of information are also relevant, given that this virtual-to-physical flow is also controlled by the Facility Manager (FM), which reveals the essence of BIM user orientation to a greater extent than usually in DT technology (Fig. 4).

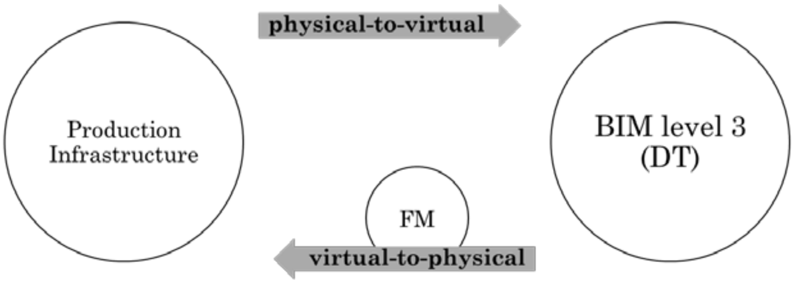

Figure 4. Bidirectionality of information flows between the real and virtual worlds using the example of production infrastructure.

The BIM level indicated in Fig. 4 corresponds to the most complete degree of development of the BIM model in accordance with the building information modeling manual [65]. The previous levels of BIM-0, BIM-1, BIM-2 are considered, respectively, as a two-dimensional non-parameterized model, three-dimensional non-parameterized model, three-dimensional parameterized model without feedback. Accordingly, the third level of BIM differs from the second by adding feedback from the virtual model to the physical (similar to the step from DS to DT). Determining the relationships in the BIM and DT classifications is one of the tools for their integration. In [61], a parallel is drawn identically between the first second and third levels of BIM and, accordingly, the digital model, digital shadow and digital twin [28], which in our opinion is very important for the development of technologies for the FoF. This proposed approach suggests that despite the different development paths of BIM and DT technologies, there are points of contact in the classification and formulation of development levels, since ultimately both technologies are aimed at forming a digital (virtual) analogue of a physical object from the real world and establishing links between real and physical object (Table 1). Here real and virtual objects are indicated by the letters R and V. It is important to note that only a few authors [61] delve into the interconnection of levels, not limited to only superficial interconnections between the technologies.

Table 1. The equivalents of the levels of development of BIM and DT technologies.

Level	Digital Twin (DT) technology	Building Information Modelling (BIM) technology
2D CAD drawings		BIM-level 0
3D	Digital Model	BIM-level 1
3D+R→V	Digital Shadow	BIM-level 2
3D+R↔V	Digital Twin	BIM-level 3

Fig. 5 schematically shows the transformation on the path from digital to virtual factories, taking into account the development of System Information Modeling (SIM) and Enterprise Resource Planning (ERP). Here we assume that at the digital factory level we are talking about creating a DT of only the first level (DT1), while omitting DT of technological processes (DT2 – DT of second level). At the smart factory level, not only the introduction of a digital twin of technological processes (DT2) is assumed, which together with DT1 forms a smart digital twin of the 1st level (SDT1), but also the establishment of feedback from a physical twin to digital twin (DS formation). At the same time, information modeling of the production infrastructure of the FoF (BIM) is gaining specific relevance. At the virtual factory level, in the first place, a system information modeling (SIM) is introduced and the degree of development of DT and BIM is increasing also. In this case, the terminology and concepts of DT1, DT2, SDT, DS are used according to the approach of the competence center of the NTI SPbPU “New Production Technologies” [9].

Obviously, with the growing demand for customized products, it is becoming more important to quickly readjust not only machines and elements of production, but also buildings and their engineering infrastructures. Therefore, when moving to the virtual factory stage, enterprise management information systems become especially important, which are impossible to realize without integration of information models of production elements (DT) and construction objects (BIM). It is important to note that while BIM regulations has already been introduced in some countries, for example in the UK [66], in terms of DT technology and the relationship between BIM and DT, there are currently no such regulatory documents.

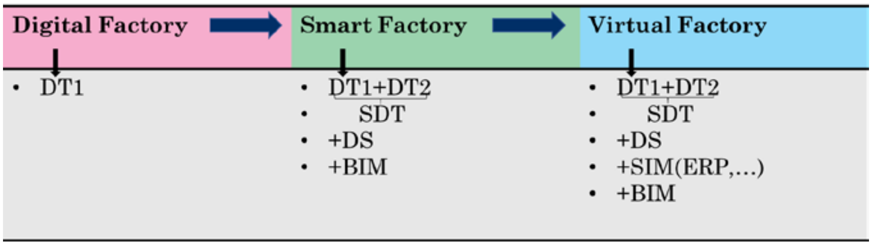

Figure 5. BIM technologies and FoF. Based on [35] with the addition of information modeling of production infrastructure – BIM.

A key factor in managing an asset such as a FoF is time. The construction object, if it is designed taking into account the possibility of subsequent reprofiling of production, change of layouts, etc., is more adaptive and flexible due to the reduction of the time of reconfiguration, which will be one of the key competitive advantages of the FoF, focused on quickly changing consumer needs. The importance of such approaches (adaptability and flexibility) is currently noted not only in the field of mechanical engineering [26–28, 67–69], but also in architecture, namely in the so-called “adaptive architecture” [70].

Due to the fact that up to the present moment BIM and DT technologies have been developing in parallel, at the moment there is no definite conceptual approach to their relationship. The relevance of this problem is growing proportionally to the digitalization of industry and the need for FoF, because, firstly, construction and production facilities are often physically inextricably linked, and secondly, the development of as-built BIM (corresponding the object in initial point in time of exploitation), as-designed BIM (corresponding planned object) and as-is BIM (corresponding actual state of the object during O&M stage) technologies is possible due to the transfer of successful experience from the field of engineering to BIM technology, in other words benchmarking from DT to BIM.

In case of the locating of the production (and, respective digital twins) within a certain production infrastructure (BIM-models respectively), there is the so-called “information silo”, which the founder of the concept of DT Greaves generally defines as the main barrier to the implementation of digital twin technology [62–64]. This means that in real situations one information system is isolated from another, although in reality their physical twins are inextricably linked. Moreover, in accordance with the theory of digital twins, in addition to the already mentioned terms DT and DS, the concept of a digital representation of some real physical component (Digital Instance – DI), created on the basis of a Digital Prototype (DP), is used. Also a set of DI, included in the digital representation of an object is called Digital Aggregate (DA) [62]). The listed technologies are located within the framework of some Digital Environment (DE) [61], which is a digital representation of the real physical environment within which the Physical Twin (PT) is operated. The BIM model for an existing facility, built on the basis of the buildings and structures corresponding to it with engineering systems included in their composition, should be considered as a tool for describing the physical environment based on data entering the virtual BIM environment, including those obtained through sensor systems. However, some of the principles of DT can be transferred to BIM modeling, nevertheless, the production infrastructure and its BIM model should be considered separately in the form of physical and digital objects, also existing within the physical and digital environments, and capable of describing the physical environment according to the principle of digital shadow and affect the physical environment according to the principle of a DT. Both in the DT and in the information model of the building, attention should be paid to all stages of the lifecycle, including the last stage - demolition [71].

3. *Results and Discussion*

3.1. *A method to integrate BIM and DT technologies for FoF*

It is obvious that in the modern world the use of 2D CAD technologies (zero-level BIM) is insufficient for organizing the process of managing construction objects [72]. BIM technologies of the second and third levels (with a unidirectional or bidirectional flow of information between the physical and virtual objects) are gradually beginning to be introduced into Facility Management (FM) practice. In the previous section, we considered the BIM classification proposed in the manual on information modeling [65]. Another common classification in the literature of BIM [15, 16, 44, 48, 59] is the division into as-designed BIM, as-built BIM (reflecting a really built object during operation) and as-is BIM (updated during the operation of the facility).

Fig. 6 shows the relationship between BIM and DT, characterizing the method that they are integrated throughout the lifecycle of FoF. The integration method involves the formation of a matrix of target indicators and resource constraints (Fig. 3) of the entire FoF as a whole, including production infrastructure, technological equipment, product and information management system. At the design and construction stage, 2D drawings and non-parameterized 3D models can be used, presented in Fig. 7 under the numbers 1 and 2. Moreover, if the designed digital BIM model is updated according to the actual construction data, then we are talking about state 3, meaning digital shadow. If, based on the results of the data obtained, adjustments are introduced into the information model that affect the real processes of building a physical asset, we can talk about DT state which is numbered 4. The real and virtual objects are denoted by the letters R and V, respectively. At the time “0” of the start of operation, we are talking about a static as-built BIM model (state 5). The concept of as-built includes the correspondence of the model to the real world (according to the results of sensors, measurements, etc.).

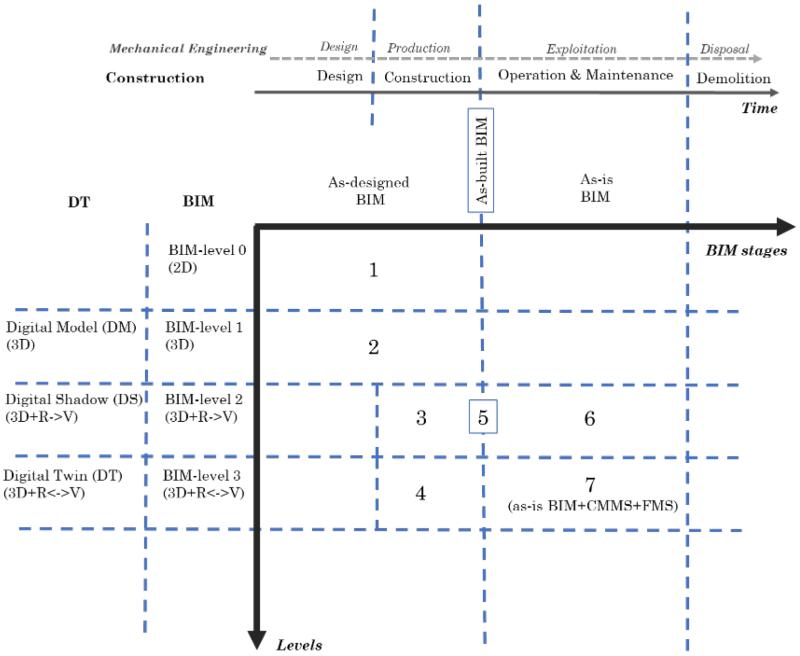

Figure 6. The method to integrate BIM and DT within the FoF: the relationship of BIM and DT levels throughout the lifecycle. (CMMS – Computerized Maintenance Management System, FMS – Facility Management System).

Since the start of operation, provided that the digital model of asset by which we understand the integrated set of information models of asset parts is updated based on the readings of the sensors, we can talk about the digital shadow of a physical construction object (state 6 in Fig.6). If, in this case, not only the conversion of objects and processes into digital form takes place, but decisions are also generated and made about the impact on the physical object based on virtual data, then we can talk about a digital asset model – a DT of asset (state 7 in Fig. 6).

The requirements for the technology of virtual factories are formed on the basis of the manufactured product, which has a minimum lifecycle in the product-production-production infrastructure chain. Therefore, as it has already been mentioned just as production must be flexible and adaptive to changes in the manufactured product, so production infrastructure must be flexible and adaptive to changing and readjusting production. But on the other hand, the production infrastructure, being the most long-lived component of the FoF, having its own lifecycle of tens of years, should be adaptive not only to transformations within the current degree of production development, but also to subsequent new technologies that will inevitably arise on the path of production infrastructure lifecycle.

It is important to note that in the current degree of development of the Architecture, Engineering & Construction (AEC) industry in case of using BIM technology at the design stage, usually, BIM technology is not implemented in the subsequent stages of the lifecycle [31]. According to this fact, the two abscissas indicated in Fig. 6 are not necessarily identically mapped onto each other. If at some stage of the lifecycle, whether it be construction or operation, the use of the updated BIM-model disappears, from that moment it becomes incorrect to refer to digital twins. Then at this moment, the owner’s assets pass into a material state only, the dualism of real and virtual also dissolves, which leads to the loss of a digital asset, and therefore a loss of tool to reduce costs (time, material, etc.). At the moment, in the absence of ubiquitous digitalization and the application of conservative methods of cost management, the need for information modeling over the lifecycle of an object is not so tangible in terms of competition, but in the future, with the emergence of modern digital cost management mechanisms, the introduction of technologies such as BIM and DT will be one of the key competitive advantages [73]. Nevertheless, at the moment, an as-designed BIM model that does not meet the requirements of a digital twin should be used in some real estate management tasks at the operational stage, such as for example space planning, provided that these tasks do not need an adequate display of physical objects and processes in numbers [74, 75]. The need to use information modeling over the lifecycle of an object so far is not so tangible from the point of view of competition, but in the future, with the advent of modern digital cost management mechanisms, the introduction of technologies such as BIM and DT will be one of the key competitive advantages [73]. Nevertheless, at the moment, an as-designed BIM model that does not meet the requirements of a digital twin can be used in some real estate management tasks at the operational stage, such as for example space planning, in case these tasks do not need an adequate display of physical objects and processes in digital way [74, 75].

In accordance with the theory of digital twins, on the basis of SDT it is possible to create digital prototype [62–64]. This is not yet a DT, as it does not have its own real physical twin (PT). We can draw an analogy that in construction, the as-designed BIM model of the building acts as DP. DI (digital instance) at the time "0" of operation in the construction industry is presented as an as-built BIM model. Subsequently, during O&M stage, the DI corresponds to as-is BIM.

According to the British BIM standard [76], all operating processes can be included in the Computerized Maintenance Management System (CMMS) and Facility Management System (FMS). Together with the BIM model of the object, they form the digital asset management information model Asset Information Management model (AIM), as shown in Fig. 7.

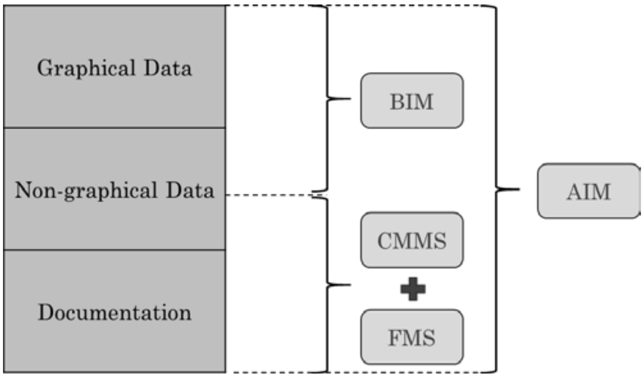

Figure 7. Digital asset management model (SDT of the first level for construction project).

As can be seen from Fig. 7, the object's lifecycle management concepts are developed, but at the same time they are considered by experts in asset management and, accordingly, solve asset management tasks. If in civil engineering projects or in commercial facilities this approach is sufficient to solve their own problems, then in case of industrial facilities there is a need to expand these concepts and link them with digital twins in the context of FoF.

If we return from the theoretical idea that the BIM model is capable of being updated at any moment during the lifecycle, including consideration and digitalization of changes in site work execution plans, operation, repair, to reality, then we can say that the continuity of the Digital Thread (this definition is borrowed from DT theory), linking all the stages of development of information model, have not been realized in construction sector yet. The Digital Thread of the construction object will not be continuous until the process of "digital certification" is established. The gap occurs at the place of formation of the as-built BIM model of the building, since in the digital field it is not the result of digital processes, but is obtained upon the from measurements and digitalization of actually built models. Nevertheless, in this situation, based on the results of SDT (following the achievements of mechanical engineering), in construction, it becomes possible to determine the necessary places for installing sensors for measuring indicators and the formation of Smart Big Data about the object. Changing a Smart Digital Shadow (SDS) that is optimized and highly adequate [77], reflected in as-is BIM model is actually a virtual tests of the construction site as a whole, which was impossible at the design stage. The most effective solution in this case is to create a public library of data taken from sensors in order to increase the level of adequacy and intelligence of the SDTn digital building twins during the design period, which means creating more intelligent DP as-designed models.

In other words, SDT, on the basis of which more and more intelligent DPs are created, on the basis of which DIs will be built, which will be combined into DAs, will be improved not only by the results of field tests of subsystems individually and virtual tests of systems and subsystems, but also due to DI changes during operation (using DS). If all such DI and DS are integrated into a common library of real-world scenarios, this will speed up the process of "clevering" SDTn of construction objects. As a result, the "learning by doing" approach will be implemented.

3.2. Digital Assets and Integration of BIM and DT Technologies

Minimization of time and errors during the readjustment of production are the main factors which represent major advantages of proposed approach and therefore must be taken into account when developing and operating the FoF. In our opinion management of these factors must be ensured by the integration of BIM and DT technologies, synchronized by data transmission formats and by time. It is the ability of quick operational interaction between BIM and DT, organized in digital environment, that allows to reduce time costs and minimize errors, which is an important competitive advantage.

Integration of BIM and DT technologies into a framework of single information model of the FoF allows to combine all the knowledge and competencies that are formed at key stages of the entire lifecycle: design, construction and operation. Thus, the information model of the FoF becomes a "digital asset", combining the knowledge base about the object. A digital asset, on one hand, must have integrity, which means to be an adequate representation of a unified physical object – the FoF, and on the other hand, have divisibility, which means that it must satisfy the requirement of sharing rights on information between participants of the object lifecycle. Integration of BIM and DT is a necessary condition for the integrity of the digital asset of the FoF in the form of an information model as a knowledge base accumulated by designers, builders and technologists. The integrity of such a digital asset implies a constant synchronization of information about the actual parameters of the FoF entities with their digital representations, as a result of which both the training of digital models and the prediction of the technical and technological parameters of the FoF throughout of their lifecycle take place.

Without a doubt the value of the digital asset can be generated through the introduction of BIM and DT technologies separately [6, 8, 11, 31, 44]. In addition to this fact their integration has multiplicativeness, which means that holistic integration of these technologies also forms the additional value for the FoF, since it is the degree of their consistency that determines how quickly and with which accuracy errors in the organization, readjustment and exploitation processes will be eliminated.

The issues of the right to own information, and in particular the issue of transferring ownership of information, the distribution of these rights among parties involved in changing and managing an object throughout its entire lifecycle, are the key issues in the theory of digital twins [61], and consequently in the theory of digital assets. If information model of production or production infrastructure is considered as an intangible resource of a company that can bring tangible benefits, for example, by reducing operating and time costs, we can consider this information model of the FoF actually as a virtual asset that has some material value [73].

Conceptually, the presence of material value in the information model was formulated by the founder of the theory of digital twins, Greaves [63], Fig. 8. In the figure, the green zone represents all the costs that are not dependent on the presence or absence of the information model, and the red and blue are additional costs in the case of absence or availability of an information model respectively. Accordingly, the introduction of information modeling technologies becomes justified at the moment when the cost of information becomes less than the totality of costs that must be incurred in the absence of this information. This issue should be considered from the point of view of added costs which a generated due to loss of information [78].

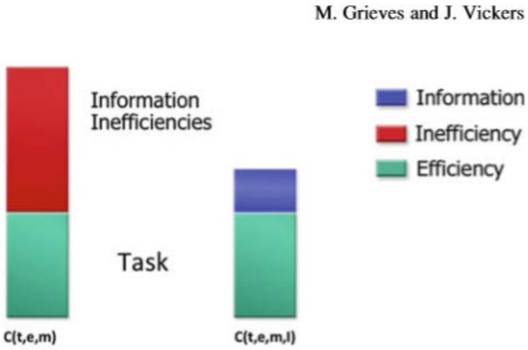

Figure 8. Information as an alternative to time, energy and material costs [63].

It is important to note that the “value of a digital asset” can be considered in two ways. On the one hand, this is the totality of all the costs spent on creating and transforming the information model over time, we denote it as C1, the blue zone in Fig. 8. Moreover, this value cannot be identified with the “value” of a digital asset, since on the other hand it is a tool for reducing costs (we denote their total cost as C2, the red zone in Fig. 8), the cost of which, to some extent, the information model goes over the barrier of the cost of all costs that were avoided due to the availability of info model and avoiding conservative methods of designing, creating and operating objects using for example CAD systems.

In addition to the conditions formulated by Greaves, under which the introduction of DT becomes profitable, we want to note that the “Information Inefficiencies” also includes the cost of errors and the absence of a quick solution to them that arise in the absence of DT, BIM and their proper integration. The ability to eliminate such errors along with time management is the key factor affecting the “value” of a digital asset.

An important further direction of research, therefore, is determining the impact of the availability and level of BIM and DT models on the value of an asset, as well as qualitative and quantitative assessment of the contribution of various participants in the creation and “operation” of this asset to determine the rights on a digital asset. In addition, it is important to consider the concept of “divisibility” of an asset and whether digital and physical assets can have different owners. In this case, the digital asset acts as an integrator, accumulating the knowledge of the designers, manufacturers and operators of the facility. To solve the described issues, first of all, a legislatively regulated method for assessing the “value” of a digital asset is needed, which should be considered as value added in the knowledge economy.

3.3. Current Implementations in the Market

The principles and methods for integration of BIM and DT proposed in previous sections are reflected in some, as yet few, projects. Some of them are presented below. It should also be noted that in our opinion these projects would be more successful if they were based on the principles and methods presented here. Some aspects of integration of information technologies into O&M stage are present in the market, but most of the time they consider only partial tasks and do not reveal connection of information models and their different layers.

Actual reports of the representatives of industry on the Going Digital 2019 conference of Bentley company state that application of BIM in the reconstruction stage of several Lipetsk iron and steel factory components has shown significant monetary savings in 3D modelling case and up to 76 days reduction of reconstruction time for the components. Therefore, even initial attempts of implementing BIM in maintenance, which is not yet the digital twin has proved its efficiency.

Practical applications of BIM in facility management [79] reveal significant maintenance efficiency improvements and cost savings. One of the indicators in above mentioned study is search for information which was reduced by 30 %. Another indicator is the time spent locating specific defective components, researching data related to those components, and formulating a maintenance plan has been reduced by an estimated 50 %. Another case study on university campuses [80] has proved that integrating BIM in facility management increases the savings on electricity consumption. The topics of energy saving also have proved to be efficiently considered using lifecycle approach [81].

Spanish company ACCIONA announced the completion of a digital twin of one of the largest desalination plants in the Middle East (the city has not been disclosed) [82]. In the process of creating a digital twin, SIMIT software (Siemens) was used. This case includes:

- remote enterprise management;
- analysis and optimization of productivity, operational capabilities in real time;
- troubleshooting and analysis of possible failures before the launch of production systems;
- comparison of data in a digital system and data in a control system facilitates validation of operations and analysis of operational capabilities;
- integration with various technologies, such as virtual reality, augmented reality, the Internet of things, machine learning

ACCIONA digital twin consists of 2 elements: an engineering design system and a control system that allows you to solve production problems in real time. This system should be connected to BIM according to the report. Creating digital counterparts meets current challenges in the field of water management, where high productivity, process efficiency and speed of installation are of great importance - said Alejandro Beivide, Director of Digital Transformation and Management Systems. He also highlights the fact that the most complicated thing about DT is to create. Probably this is one of the major barriers in digitization of industry.

Currently Saint Petersburg Polytechnic University is also working on integrating DT solutions into ERP system according to actual requests from industry.

Another challenge in this case is that costs associated with training building information modeling personnel apart from the initial investment cost, sufficient time and human resources must be allocated for training building professionals to use BIM [83]

According to current state-of-the-art of the issues there are several gaps that remain unsolved due to the absence of complex concept approach which is discussed in this article. We consider approach which includes involvement of BIM & DT integration to be the tool to bridge existing gaps on the way to digitization of industrial assets.

4. Conclusions

This article is devoted to the study and development of principles and methods for integrating digital twin technologies and building information modeling in the context of the FoF. Convergence efficiency of BIM and DT is considered. The barriers to the integration of BIM and DT technologies are investigated and ways to overcome them are presented, based on the form of BIM and DT relation shown in Fig. 6.

Both BIM and DT technologies are informational, focusing on creating information models of physical objects and processes that are highly relevant to the real world, but at the same time they have been developing in parallel in the fields of construction and mechanical engineering. In the context of future factories, BIM and DT refer to the same physical entity. The key difference between BIM and DT technologies is the degree of detail of information models, in particular, DT technology implies full digitalization of technological processes, as well as the presence of a bi-directional information flow between a real and a virtual object, and BIM technology in this sense is less developed. However, BIM technology in a number of countries, such as the United Kingdom, has gradually been consolidated in regulatory documents over the past ten years, which cannot be said about DT technologies. Thus, the following basic principles are proposed, on the basis of which the integration of BIM and DT technologies within the framework of the FoF should occur.

The first principle: the integration of BIM and DT technologies should ensure the design, construction and operation of FoF, taking into account the needs of production in the flexible restructuring of production technologies based on changes in consumer needs. In this case, specific implementations of the integration of BIM and DT technologies are formed on the basis of the manufactured product, which has a minimum lifecycle in the product-production-production infrastructure chain. Therefore, just as production must be flexible and adaptive to changes in the manufactured product, so production infrastructure must be flexible and adaptive to changing and rebuilding production. But on the other hand, production infrastructure, being the most long-lived component of the FoF, having a lifecycle of tens of years, it should be adaptable not only to transformations within the framework of new production needs arising from the release of a new product with a different DT, but also to possible other new technologies that will inevitably arise along the path of the production infrastructure lifecycle.

The second principle: the integration of BIM and DT technologies should ensure the validation of “smart” models for the formation of a highly adequate digital model of the FoF based on both virtual and full-scale tests. This principle is based on the positive experience of digital twin technology, which is characterized by the performance of tens of thousands of virtual tests for each component (assembly, part, mechanism, interface, etc.), materials and the whole system. In the case of BIM technologies, there is experience in virtual tests to validate the model, but full-scale field tests are possible only at the level of a part or a separate system, while testing of the entire building or structure only possible during operation. In this regard, integration of BIM and DT technologies requires the accumulation of experience in the construction and operation of complex technical objects and the filling of a field test database using sensors and digital shadow principles (information flow from a real object to a virtual one), as well as maintaining the relevance of the information model throughout the lifecycle and maintaining the continuity of the Digital thread.

The third principle: in the aggregate, BIM, DT, SIM, and other technologies are designed to form a digital asset – a digital resource of the owner of a physical asset that brings (or can bring, when used correctly) economic benefits throughout the lifecycle of an object in the form of reduced transaction costs, time and material.

Based on the stated principles, the method for integrating DT and BIM technologies in the context of FoF has been formed. The integration method involves the formation of a matrix of target indicators and resource constraints (Fig. 3) of the whole FoF as a whole, including production infrastructure, technological equipment, product and information management system. A highly adequate to real world, tested and validated information model of the FoF should be created to reduce material and time operational costs. The model must support the flexibility and adaptability of the factory, reflecting the properties of objects and technological processes and be capable of influencing physical changes in the objects and processes of the factory throughout lifecycle. To create such model, it is necessary to follow the sequence of synchronous transition from level to level for the coordinated simplification/complication of virtual models created on the basis of BIM and DT technologies, shown in Fig. 7. Thus, since this study primarily addresses the issue of integrating BIM and DT technologies in the concept of FoF, an appropriate method should be based on the interaction points indicated in Fig. 7.

Analysis of the literature showed that the main barriers to the development of DT technology are related to the ownership of data and information in DT technologies and the integration between virtual objects described by DT. These are just some of the problems identified during the study, but other gaps in the development of digital twins are assumed; this article focuses primarily on researching and developing ways to integrate technologies. Therefore, the urgent direction of further research, based on the identified problem of data ownership, is the development of information management systems (SIM) for FoF. It is noteworthy that in the field of BIM-technologies, this particular issue (information ownership) is the key subject of discussion of currently emerging regulatory documents, such as ISO-19650, Part 3, associated with the operational phase of the BIM project and existing ones, such as ISO-19650, Part 1,2, associated with the design and construction stages.

Existing barrier related to the integration between virtual objects described by DT was partially considered in this article. In this case, the BIM model and the DT are considered as virtual objects, between which the so-called “information silo” arises. The actual direction of further research will be the study of technical ways of implementing the developed approaches. At the moment, in some cases, software is developing faster than the real industry representatives need such software. It is necessary to establish a connection between the developed approaches and the real ways of introducing BIM and DT technologies in complex technical objects.

Transformation of a digital asset is a separate issue that requires careful consideration. In this article, only a preliminary definition and structure of a digital asset is given, but it is necessary to understand that a digital asset is a complex time-transforming resource that does not belong entirely to one person, but is distributed among all participants in the design, production, construction, operation and destruction or demolition of physical objects.

An important area of further research is the issue of ownership and distribution of rights in relation to a digital asset, its integrity and divisibility. The integration of information modeling into Future Factories reduces time and minimizes the errors associated with quick readjustment of production. Based on this, BIM and DT models, as well as their consistency, add “value” to the FoF, which means that it is necessary to consider a digital asset as an integrator of knowledge accumulated by all participants in the lifecycle of an object.

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