Digital Thread and Building Lifecycle Management for Industrialisation of Construction Operations: a State-of-the-Art Review

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Abstract. The construction industry is changing its practices to adapt to its contemporary context. The rise of Building Information Modelling (BIM) is disrupting the way a construction project is thought and managed. To support this evolution, inspiration is taken from manufacturing industries practices which have faced similar challenges. The goal is to develop a more industrialized way to build in order to better manage quality, costs, delays, and to improve working conditions. This article develops the main challenges to face so to achieve this transformation through a literature review. BIM can be compared to the Product Lifecycle Management (PLM) system in manufacturing fields. BIM could be further developed by changing its unique data structuring into a PLM-inspired organization to adapt representation to the project's stages and stakeholders needs. Data management also allows more detailed simulations of site operations, highlighting the current planning practices limits. Finally, developing a data-centered approach to manage and produce facilitates early and cross-disciplinary cooperation. This reorganization supports the application of heterodox production methods like off-site construction. As a whole, industrializing construction demands to develop a holistic vision of a facility lifecycle, which can only be developed through better communication and more collaborative practices, bolstered by a more developed digital model.

Keywords: Building Information Modelling (BIM), Product Lifecycle Management (PLM), 4D, off-site construction, Design for Manufacture and Assembly (DfMA).

1 Introduction

The construction industry is undergoing its digital transition as Building Information Modelling (BIM) is disrupting the way professionals produce technical documents and manage a construction project [1, 2]. BIM is defined as the development and use of a digital information model to represent a facility in order to support decision making throughout its lifecycle [3, 4]. Moreover, the industry has been facing many challenges for several years: e.g., cost management, time management, waste management. This can be partly explained by the evolution of socio-economic and natural constraints and the seeming lack of evolution in practices [1].

Given these considerations, there is a need to transform the way we build through a more extensive use of digital information and processes. Fortunately, other industrial fields have been refining these practices for many years and seem better adapted to their contemporary constraints than construction companies thanks to the concept of Product Lifecycle Management (PLM) [5, 6]. Therefore, a starting point of this transformation is to learn from these practices.

In this paper, we ask what are the means of industrialisation of the construction industry leveraging the use of digital solutions. Firstly, we will analyse the interactions between BIM and PLM. Secondly, we will synthesise the development of 4D BIM uses to transform site management. Finally, we will study off-site construction methods to understand how this type of production impact a project's lifecycle. In other words, BIM is remodelling how we represent a facility, how we organise work to create it, and how we produce it.

2 PLM contributions to BIM development

2.1 How to leverage PLM to enhance BIM?

BIM is seen as a mean to face the many challenges of the construction industry. However, developing this technological concept remains a complex task [7]. Academic research has primarily focused on its technical aspects by working on necessary topics for its development such as Industry Foundation Classes (IFC) exchange formats [4, 7]. Although important, this is not enough to fully change the industry practices. Since BIM represents a paradigmatic shift in design and production, it must be treated as such. One of the main challenges is to deploy these techniques and practices throughout the lifecycle of a structure [1].

Similar issues in the manufacturing industries gave rise to PLM in the 1990s [8, 9]. PLM can be defined as a holistic business concept to manage a product and its documentation during its entire lifecycle [8]. Therefore, PLM is seen as an inspiration for the development of BIM [6, 10, 11]. However, the possible links between the two concepts remain unclear [5]. Implementing PLM solutions directly in the construction industry is not relevant because it is tailored to a specific industrial context [6]. Moreover, there is no established consensus on how to apply BIM, no matter a facility lifecycle stage [6, 7, 10, 12, 13], let alone on how to draw from PLM practices [5].

Thus, there is a need to develop a BIM strategy for the entire lifecycle of a structure. Drawing from PLM practices, it could be possible to develop a system called building lifecycle management (BLM) [5, 14]. A first point of entry could be by managing a project's data during its different stages through the digital mock-up [15].

2.2 Managing data classification to represent a project's evolution

The creation of a BIM model depends on the classification of its elementary components, as BIM is object-oriented [1]. Several classification formats exist, each one proposing its own approach regarding the issues addressed [13]. Yet, only IFC and Omniclass formats take into account the entire lifecycle of a facility [2]. However, the core principle of every classification is the same: a work is composed of elementary units whose level of development varies according to the project's stage. This composition has several names in literature: model element table , model element breakdown or product breakdown structure (PBS) [11]. PBS represents a work by stating its components, their relations to one another, and their level of development (LOD) at a given stage of the project [11]. Here, we define a construction project as the set of actions framed and developed to produce a facility [16].

This data classification can be compared to those used by the manufacturing industries [15]. Indeed, a manufactured product is developed partly by defining it, throughout design and production, thanks to specific views. Each view is based on an adapted bill-of-material (BOM) which describe the component of the product at a specific stage. BOMs and their variations represent the product structure (PS) [11, 17, 18]. As a project advances, new BOM are created and PS become more detailed to meet specifications. Most notably, engineering BOM (eBOM) and manufacturing BOM (mBOM) are respectively list of materials for the "as designed PS" and "as planned PS". Each component of a PS is defined by its relations to the others and by its metadata. By assembling all of these information together, PLM systems are able to create dynamic specific views of the product according to the user role and needs [17].

The manufacturing classification approach appears more developed and holistic compared to that of the construction industry [2, 15] as it offer multiple dynamic views of a same product compared to the static ones founded in BIM [18]. Thus, PS could be a starting point to develop BIM by modifying a mock-up PBS according to the stages of the project and the mock-up uses.

Be that as it may, classifying BIM data could be thwarted by the lack of consensus around BIM uses which could highlight the challenge to specify the technical aspects of a facility according to modern practices [6, 10, 13].

2.3 Requirement and change management to support data structuring

According to Bérard and Boton [13], there is currently no effective solution to link the digital mock-up and the project requirements. This hinders the project management as it is difficult to check the required levels of information and detail of the mock-up. This problem could be explained, partly, by the challenge to technically define the project early on and the lack of consensus on BIM uses [10, 12, 19, 20]. There could also be a lack of formalism to define the requirements impeding the transformation of a conceptual work into a technical execution [19]. It seems that materialising a facility requirements into a digital mock-up is a more formalised practice in manufacturing industries which, nonetheless, is based on the same principles [19]. Here, a definition of the work similar to the PS could help to define and to structure its requirements with the right level of information at each stage of the project [2]. Such an information classification would ensure data continuum all along the mock-up lifecycle [8, 9, 18, 21]. Therefore, the management of the digital model and of the project are facilitated [13, 19].

However, doing so require a cross-functional cooperation to manage a project both from a process and a data perspective. Aram and Eastman [6] show that PLM systems achieve this cooperative digital continuum by handling a project through the management of its mock-up's evolutions. Indeed, configuration and change management are central parts of PLM practices [22]. Doing so imposes to develop an interdisciplinary reflection on a problem and its consequences all along the project's lifecycle [6, 22]. BIM processes could benefit from such a data-centered point of view [11] which bolster cooperation and performance by focusing on managing the information needed to carry the work [23].

As shown, developing data model for a facility demands to establish a digital continuum to better comprehend its lifecycle. This digital thread forces stakeholders to think about design and production with a different temporal point of view as they must manage the facility lifecycle and its data lifecycles in parallel, both being different. This also induces to develop a data-oriented approach of the project management. In the next section, we will discuss how BIM is impacting site management, and how it modifies work execution.

3 Improving site operations management with 4D BIM

3.1 Why would we need 4D BIM?

Planning is an essential activity for the smooth running of a project. It is even more so in the context of construction which involves many participants in a unique context. For this reason, many planning methods have been adopted by the industry to coordinate stakeholders. Nevertheless, methods such as the Gantt chart or the PERT chart have their limits [20, 24]. Indeed, adaptation capacity of traditional management practices seem limited when facing disruption, whether considering design or operation stages of a project [20, 25].

According to Sriprasert and Dawood [24] site planning and management methods lack a systemic approach to deal with work execution and rely on corrective actions rather than favoring a continuous improvement process.

Based on these findings, improving site management methods seems necessary [25]. Thus, digital solutions are seen as a way to take into account all the constraints of planning and managing a site, while facilitating communication between all the members of a project [20, 24, 26].

3.2 4D BIM: general principles

The primary objective of 4D BIM is to add a temporal notion to the digital mock-up in order to analyse the site evolution, and the construction processes [26]. This model creates a common ground for stakeholders to manage work execution. By doing so, processes optimisation is decoupled from the sole user experience [26].

In its most simple form, a 4D model is created by linking a 3D representation of the facility to the planning [24, 27]. Boton [26], notes that a 4D model needs to structure itself around the LOD of the visual representation and the LOD of the operation processes, each one being independent from the other. This cannot be done without the stakeholders' collaboration. [26].

This cooperation is bolstered by several uses defined throughout academic literature [28, 29]. Those uses allow professionals to analyse a construction site during its preparation as well as during its progress, according to both a process and resources point of view [30]. An emphasis is placed on predictive analysis, which seems to be lacking in the usual practices of the industry [28, 29].

However, the development of 4D BIM is not yet complete and some barriers still need to be removed for it to reach its full potential.

3.3 An overview of 4D BIM research development

Creating a 4D mock-up as described above has its limits because this approach is not sufficient to surpass conventional management logics [31]. This technique offers a single vision of the construction processes to all participants [26]. However, depending on the roles and tasks considered, the information needed are not the same [31]. As a result, it is necessary to produce views adapted to each one of them [29, 31]. Moreover, this multiplicity of views could favour collaboration, and bring 4D BIM uses closer to those of model-based system engineering [26, 32].

Furthermore, it should be noted that 4D BIM mainly considers the temporal evolution of the site, while neglecting its spatial evolution: i.e. operations are optimized solely by comparing schedules [30, 31]. However, a 4D BIM model can also include resources and their flows to represent the site's evolution [27, 29–31]. Such modeling allows for a dynamic site layout which can work as a basis for production management through the control of spatiotemporal conflict within the site [29–31].

Thus, the 4D mock-up is no longer a simple visual representation of the construction site evolution, but becomes a database used as a decision support system to monitor and to manage operations through optimisation algorithms, while allowing continuous improvement processes [29–31]. The provisional schedule obtained would be more precise than a traditional one, and would allow a more realistic analysis while taking into account more parameters than before [26, 30].

So far, we focused on the technical development of 4D BIM and its uses. However, another challenge remains: implementing these practices on the field and facilitating their appropriation throughout the industry.

3.4 The challenge of 4D BIM implementation

As we have seen, knowledge about 4D BIM is undergoing an important development. Yet, the grasp on this concept is mostly limited to the academic world and leaves out the reality of the professional world. Indeed, most BIM uses are currently limited to the design stages [33], and the digital model has yet to take its place on the field [10, 33, 34]. Hence, to bolster the development of 4D BIM researchers and professionals are teaming up to bridge this gap [32–34]

Furthermore, managing a construction site demands to plan and to monitor several operations at the same time, while maintaining true to the schedule and budget. Theses constraints make it difficult to try out new processes and solutions as they disrupt well-proven methods [10, 33]. This is currently done by dealing with heterogenous information across various documents [32]. Hence, a 4D digital mock-up cannot limit itself to a visual representation of the structure to be fully useful. It needs to take into account all the information or metadata surrounding the operations, in order to improve on the existing solutions [20, 32, 33].

4D BIM modify the way to represent and to manage a site. This digital approach to production hints towards management systems already in use in other industry like a model-based project management [26, 32], or a PLM system [10]. To bring professional applications of 4D BIM closer to the academical ones, the information needed to represent, to manage, and to communicate about the site operations need to be arranged in a new way to make them practical [10, 32, 34].

Although 4D BIM modify conventional management practices, it doesn't question the way we produce. Yet, thanks to these digital solutions construction methods can also be transformed and brought closer to a manufacturing approach. In the next section, we will analyse how to transform building execution work from an on-site "craft work" into an off-site industrialised work thanks to a data-oriented project.

4 Off-site construction: an opportunity?

4.1 Why would we need to build off-site?

The construction industry productivity is considered to be slower and lower than other industries since several decades [35] and little change have happened over the last 20 to 30 years in its building methods [25]. Moreover, this industry is one of the main producers of waste in the world [36, 37]. Waste generation can stem from various sources, e.g. poor design, poor planning, or poor change management [37], which reveal a need to improve quality management over a product's value chain. Improving quality management would be beneficial both from an environmental and financial standpoint [36]. Furthermore, construction sites are known to be dangerous places, with strict security measures nonetheless, not always organised to ease operations. Off-site construction is seen as a mean to face all of these challenges at once [38–40], while also improving working conditions for site workers. Shifting operations into a controlled environment such as a workshop would allow for a safer work environment, and for a more precise management of resources and processes.

However, off-site construction cannot be done with on-site methods [41]. To bring production outside of the site, design and execution management need to be modified. This change can be supported by a BIM system [37, 42], and can draw from manufacturing production methods [41, 43].

4.2 A holistic design approach to support lifecycle thinking

Decline in quality can often be linked to problems emerging from the design phase, as shown above. Moreover, off-site construction imposes a specific approach to deal with production sequences, supply chain, and installation, which need to be tackled from the design stage [41]. Hence, rethinking the design approach could transform production methods [42]. A design strategy needs to be applied to conceive a product adapted to every stage of the project lifecycle, or to solve a particular problem along the production line [44]. Several techniques exist and can be combined together: e.g., design for manufacture and assembly (DfMA) or design for deconstruction (DFD) [38, 41]. These techniques take inspiration from the manufacturing industry which face similar challenges to produce goods [41, 43]. To do so, the later developed a solution-oriented multidisciplinary procedure to accommodate every stakeholders needs from the beginning [43, 45].

However, digital mock-ups and simulations play a critical role to anticipate issues along the line [9, 18, 21, 45]. Oriented design development in the manufacturing world depends on a PLM system to function. Therefore, a similar approach in the construction industry is needed [41, 42]. This way, the technical documents give a more realistic vision of the future work. Leading to smoother communications, and facilitating production [41, 44, 45]. Nevertheless, switching to new production methods also demands new management methods [35, 43].

4.3 How to support an off-site construction project?

Off-site construction has been around for a long time [46], but its use in the building sector has gained interest in the past decade. Hence, there is few knowledge surrounding its large-scale application in a contemporary context [35].

Off-site construction encompasses several production methods, as there are many ways to produce buildings parts in a plant, e.g. kit of parts or complete sub-systems known as modules [43]. Depending on the chosen methods, management practices can differ. Nevertheless, there are common basis to managing such productions [35, 43]. Indeed, producing in a plant imposes to think about the processes along the production line and the supply chain, as well as the execution methods on site. Several critical success factors have been identified in literature to face these challenges [35, 43, 46]. The design stage is crucial because decisions at this moment ripple on the following project's stages [35, 42, 45]. This demands to settle for a design solution earlier than usually to better manage changes if they occur [47, 48]. Hence, to minimise conflicts, stakeholders must intervene and cooperate early in the project [43, 46]. Moreover, there is a need to plan production according to a product-process-resources point of view to further develop this holistic approach to production [35, 43]. Through these recommendations, we see the need for an earlier and stronger implication of stakeholders in a project. This cooperation can only be effective if a strategy is developed to reinforce this choice of production [46]. Traditional project organisation and management methods can no longer be used and must be adapted to this new production ecosystem.

5 Summary and future works

This paper has developed the main challenges and considerations underlying the current transformation of the construction industry. As Building Information Modelling is becoming more and more developed and used, business practices are changing. Thanks to this disruption, and in response to the evolutions of its ecosystem, the construction sector is transforming its practices towards more industrialised ones. By drawing inspiration from the manufacturing fields, we see the need to further develop the BIM data structuring. A unique static vision of a digital mock-up is not enough to support communication and decision making during a project's lifecycle. Data must be organised according to the project's stage and the specific needs of the stakeholders. Such structuring changes our temporal conception of a project. This need for data management also highlights the limits of current production planning methods. BIM allows to manipulate more and more information to represent, to simulate, and to optimise a project, yet this demands to develop new practices for professionals, especially during production stages. This can be bolstered by appropriate data structuring. Finally, through the considerations of data management and operation planning we can develop new building methods such as off-site construction. Traditional practices seem outdated to face current challenges and need to change to take into consideration new concepts and new solutions. Transferring execution work off-site have several advantages but impose to use different approaches from the design stage to on-site implementation. Here, once again, manufacturing practices can be a source of inspiration. In this case, interdisciplinary cooperation around a digital model is the key to anticipate difficulties and to achieve satisfying results for all.

Given all these considerations, the authors will continue their work by investigating the development of a PLM-inspired BIM model. Such a model aims to represent a facility according to different points of view in order to optimise its execution while taking into account the new way of producing and managing a work discussed in this paper.

6 Acknowledgments

The authors would like to express their gratitude to the feedback given by Spie batignolles reviewers.

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