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Impact of Intelligent Product and BIM4D technologies on construction site monitoring: an experimentation framework

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Abstract. Industrialized building process has encouraged the utilization of new Information Technologies to boost the productivity and quality of construction projects. The use of the BIM (Building Information Modeling) technology combined with real time monitoring of the construction site could improve the planning throughout the building lifecycle. In the framework of the ANR McBIM Project, intelligent building products made of communicating concrete are currently being designed. These products, equipped with micro-electronic devices, can report their statuses in real-time. This paper thus investigates the use of such products combined with BIM technologies and explores the potential benefits in terms of cost for the management of construction sites, depending on their organization pattern.

Keywords: Building Information Modelling, Real time monitoring, Building lifecycle, Planning.

1 INTRODUCTION

The AEC (Architecture, Engineering and Construction) sector offers highly customized products and services with an engineer-to-order approach to markets. However, to enhance productivity, quality and sustainability, there is a real trend towards the pre-fabrication of components and modular construction approach. The goal is to meet the architects and customers' demands while enjoying the benefits of workshop manufacturing and mass production. Just like every other industry is leaning towards digitalization, the construction industry is no exception. With the introduction of new technologies to the construction world, the scheduling and the tracking of the work progress are revolutionized. Unlike the manufacturing industry, the AEC sector has a completely different approach for planning and scheduling activities. Traditionally, after the definition of the project requirements and the design of a master planning, the project is

then structured into lots (sub-products). This structuration provides a top-down hierarchical view of all of the products/components (outputs) within a project. This makes it easier to ensure that all the outputs and relative activities have been identified before going into the detail of identifying the work packages or activities within a Work Breakdown Structure (WBS). Specialists then carry out their own iterative design while taking into account changes made by other stakeholders. The exchanges are numerous, and the formats of exchanges are varied (El-Haouzi, Derigent et Thomas, 2019) that could lead to a desynchronisation between the initial planning and the real situation.

The McBIM Project (Material communicating with the BIM - Building Information Modelling) (McBIM Consortium, 2018; Derigent et al., 2019) aims to design a “communicating concrete”, defined as an instantiation of the communicating material paradigm (Derigent, Mcfarlane et El-haouzi, 2020). This communicating concrete consists of a concrete structure where many sensing and communicating nodes are spread. Communicating nodes aggregate received data and transmit them to remote servers thanks to BIM standards. A large volume of product information is thus imagined to be available and could then be used during the construction progress of a construction site.

In this paper, we assume that intelligent products (communicating concretes and other ones) are present on the construction site (the means to realize this vision is outside the scope of this paper). One interesting question is then to *validate and evaluate the importance of having such information during the planning process in a construction project*. Indeed, validating the usefulness of this information can help to promote the use of intelligent products in the construction industry. In this work, only intelligent products of level 1 in the sense of (McFarlane *et al.*, 2003) are considered. This paper addresses this question, and is organized as follow: In section 2, a presentation of the state of the art will be done. The section 3 presents the proposed methodological approach, and an application case is described in section 4. Finally, the last section draws some conclusions and outlooks.

2 STATE OF THE ART

Buildings are complex systems, and multiple stakeholders, with different skills, must be synchronized to achieve their construction in the required amount of time and money. Therefore, construction planning/scheduling and monitoring are key aspects of a construction project. In the following state of the art, these two aspects are studied in the sections 2.1 and 2.2 respectively. In a last section (2.3), 4D BIM tools are introduced since they provide graphical interface to understand visually complex schedules but also because they could be used to transform product location (e.g., where is my product *X*?) into planning information (e.g did my task *Y* end?).

2.1 Scheduling based on real-time information

With the introduction of information availability, it is interesting to study the effects of having the information to improve construction planning. (Szczeny et König, 2015) proposes to get actual logistics data on the site condition and to adapt the schedule

accordingly. The concept consists mainly of four steps: logistics data acquisition, data preparation using a defined and reasonable probability distribution, creation of a simulation model and finally analysis and decision making. In order to generate a feasible schedule respecting different objectives, NSGA-II genetic algorithm is adopted since the authors claim its superiority among other multi-objective optimization algorithms. The current data of the site contains information regarding delivery status of materials and progress of each activity, any disruption being reported. Once the data is collected, the new schedule can be generated. The implementation of this system shows that having even minimal information about the site status can improve the project execution efficiency. However, in their work, the data collected is rapidly outdated due to infrequent collection.

With the validation of the importance of available site information, new scheduling approaches emerge. (Dallasega *et al.*, 2019) proposes a lean method combined with real time monitoring, known as the “agile schedule”, where the fabrication shop is working in a traditional pull system, the semi-finished products are manufactured based on master production schedule (MPS) approaches and stored. Once the products are needed at the installation sites, the semi-finished products are assembled and delivered. The final assembly of the products is triggered by demand in real time, the installation sites must request the needed material four weeks in advance. An order backlog collects all the demands and prioritizes them to avoid any clash between installation sites. At the beginning, the foremen of the site need to communicate the information regarding delays, or any kind of disruption and the backlog list will rebalance itself autonomously. This agile schedule improves the stay on site time and reduces the buffer sizes significantly, although it didn't have much effect on the lead time.

2.2 Real-Time monitoring systems in construction project

A construction project is inherently prone to delays, due to the complexity of the construction environment. Without real-time information, initial schedules could rapidly become unreliable. Moreover, since the planning fails to represent the actual state of the construction site, unexpected events and related delays cannot be detected, which prevents any reaction when events occur. When talking about Real-Time (RT) monitoring, two types of approaches have been identified in our state of the art, classified as external or internal monitoring. The external RT monitoring technique consists of continuously tracking the site from using additional external tools as 3D scans or drones, where the internal RT monitoring technique requires equipping the desired elements to be traced with sensors, making the construction site self-monitoring.

When considering external RT monitoring, one of the most promising approaches is the Scan vs BIM proposed by (Pučko, Šuman et Rebolj, 2018). This method relies on low precision 3D scanning devices installed on workers' protective helmets capturing the state of the active site continuously and recording partial point clouds which are later on merged into a complete 4D as-built point cloud of a building under construction. The 4D as-built model is compared with the 4D as-designed model using Trimble Vico Office (a BIM Project Management Software). The output is a list of elements

that are either built ahead of time or not built yet. This comparison allows the identification of any difference between models. This method enables the early detection of deviation in the schedule plan, although this approach had some problems with precise positioning and orientation and time consumption.

(Naticchia, Vaccarini et Carbonari, 2013) proposes an internal RT monitoring via a ZigBee approach to create a system composed of active tags coupled with a network architecture. The system is implemented to track the progress of the construction site and provide valuable information in real time in order to facilitate the work of the site health and safety inspectors. The site coordinators provide a list of workers coupled with the data regarding the areas in which the workers are allowed to operate or pass through. The system is thus able to record all unauthorized passes. The collected data analyzed by the coordinators provide a visualization of the work progress in real time. The system can alert any unexpected behavior and helps to improve the overall health and safety all while improving the accuracy management and quality control. The only problem with this system is the low accuracy and precision, since it provides zoning instead of positioning which limits the application to cases where position tracking or only minimal information is required. In real life applications, this later approach is often encountered, as developed more extensively in the McBIM Project.

2.3 Scheduling based on 4D BIM tools

Site planning is a crucial design tool to visualize and organize the workflow in a construction project. With the considerable increase of construction projects complexity levels, the traditional approaches such as Gantt charts are not able to provide an easy-to-read schedule. Indeed, when the project becomes too complicated, all the planned tasks cannot be visible in on view and could prevent to understand the overall workflow. More importantly, the lack of coordination between actors can cause major problems on site. 4D BIM methods can help to solve these two problems. The term *BIM* means “Building Information Modeling” and refers to the computerized modelling of a generic building construction, and the term *4D* refers to the fourth dimension i.e time. This technology is based on organizing all the information about objects (Vignali *et al.*, 2021), by associating time-related information to 3D models to enable the visualization of the sequence of construction operations (Heigermoser *et al.*, 2019). Hence, each element can be visualized and attached to a certain task in a given schedule. Moreover, the 4D model allow the visual representation and assessment of the entire work progress and the detection of potential problems at early stages. Compared to traditional planning, the 4D simulation is proven to be more time consuming by 20%, but offers a 40% improvement in visual control of the workflow and data update process (Candelario-Garrido, García-Sanz-Calcedo et Reyes Rodríguez, 2017). 4D BIM tools can then provide a link between product location and task completion.

2.4 Challenges and Problem statement

Till today construction site planning is considered as one of the most complex dilemmas of a construction project. The traditional methods helped improve the scheduling process by introducing the lookahead approach to increase the flexibility of the schedule. Furthermore, with the increase of construction projects complexity, the 4D BIM technology has been introduced to enhance the visualization and overall understanding of the project. After the advances made in the wireless sensing fields, some initiatives have tried to deploy real time monitoring technologies in a place where uncertainties are bound to happen. Many approaches were developed in order to track the site situation, unfortunately all of them presented some weakness in terms of tracking precision, data quality and information accuracy. Moreover, given that the topic of real time monitoring of construction sites is still new, not enough studies were conducted regarding the added value of having the information, nor there is enough research regarding the effect of the information extraction frequency on the validity of the information.

Therefore, the aim of this paper is to test a new method combining the BIM technology with the IP and show the benefits of having the information on the overall project cost. In addition to that, the impact of the information extraction frequency will be studied.

3 Proposal

Given what was stated above, the interest in this paper is to verify the importance of having the information on the planning in a construction site. Moreover, the information availability is not the only key factor for improving the site logistics, the information extraction frequency is just as important. Since the objective of this paper is to show the interest in implementing the IP, only the effect on the storage and resources costs were considered when conducting this study.

3.1 System logic

The specific application described in this paper was intended to show the possible benefits of a real time monitoring system, which functions by continuously communicating information regarding the location of the materials (via innovative techniques developed in the McBIM Project). This information can help to keep the entire construction site under control. Material location is supposed to be provided by every IP on the construction site.

The proposed approach (see figure 2) is inspired from (Pučko, Šuman et Rebolj, 2018). It requires the existence of 4D BIM models based on an existing schedule. Two different models are considered: the 4D model based on the initial schedule is noted as the 4D As-Designed BIM (4D AD BIM), and the 4D BIM updated with RT information is identified as the 4D As-Built BIM (**4D AB BIM**). The IP shares wirelessly the location of the material which is collected and stored in a database. At the end of each day, location information regarding the site situation is used to update the 4D AD BIM,

which is then compared to the 4D AD BIM to obtain the differences and as a result the tasks experiencing some delays.

As an example, let a wall *A* that is supposed to be at place *X* at the end of task 5, arriving at $t=t_1$ (figure 1). Thanks to the 4D AB BIM, the whereabouts of wall *A* is precisely known. So, at time t_1 (when the task 5 is supposed to end), two possible situations can arise : either *A* gives the information that it is installed in *X* which will mean that everything is running smoothly, or *A* gives a different location, which means that some disruption in schedule is taking place and the supervisor need to intervene immediately. This process will remain until the end of the construction project.

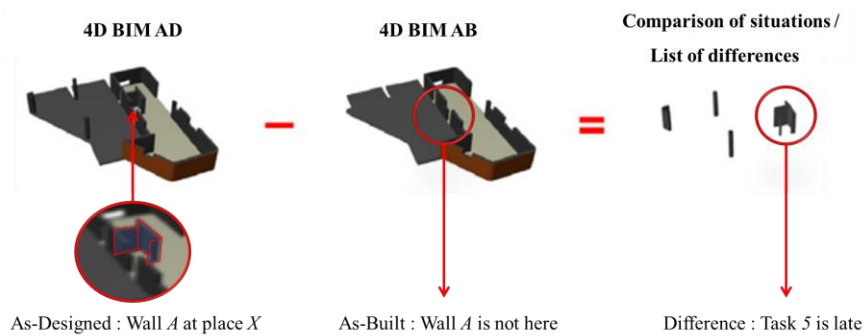


Fig. 1. Difference between 4D AD BIM and 4D AB BIM and the resulting elements, adapted from (Pučko, Šuman et Rebolj, 2018)

3.2 Detailed 4D BIM AD VS 4D BIM AB procedure

The 4D BIM AB represents all the elements in the construction project that are already built up to a certain point in the schedule. Any disruption of the planning can be easily detected by conducting a simple comparison between the 4D BIM AD and the 4D BIM AB. The difference between the two is a list of elements that are not following the schedule, as depicted in figure 1.

If the list is empty the project is thus on the right track, otherwise some decisions need to be made in order to restore the control on site. As said earlier, every element in the 3D model is linked to a task in the project planning, meaning each element represents a point in time in the schedule. Indeed, a missing element is an indication of a disruption in the planning.

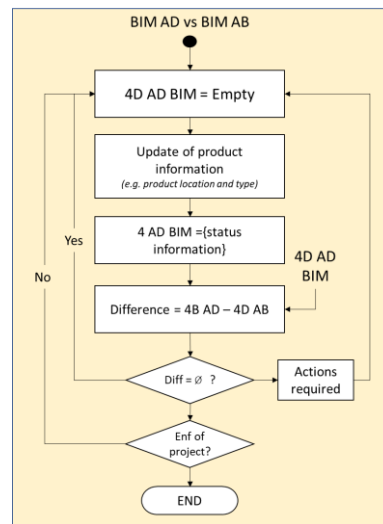


Fig. 2. BIM coupled with product information, adapted from (Pučko, Šuman et Rebolj, 2018)

4 Case Study

In this case study, we propose to validate this approach by simulating a construction site. Research has shown that construction materials and equipment may constitute more than 70% of the total cost for a typical construction project (Sangotra et Lende, 2020). Since the factor taken into consideration in our study is the total cost of the project, our case study will focus on these types of cost. The construction to build is based on the lean game applied to construction developed by ENSTIB and CRAN with CIPE. In an attempt to address the issue of the rising cost of building activities, construction sites began to leverage the information for the redesign of new material logistics plan (Sangotra et Lende, 2020). Following this idea, this case study also encompasses different logistics plan going from a traditional push system to an agile planning. Both points, construction building and site logistics, are described hereafter.

4.1 Presentation of the Lean Construction Game

The aim of this game is to compare the traditional construction methods to the lean one by simulating the construction process of four wooden houses denoted A, B, C, D. These houses are composed of prefabricated panels assembled on site. A fully detailed study was conducted and information regarding the planning, human resources cost, material cost, equipment cost, and delay penalty cost are available.

The 3D model consisting of a replica of house A and D (as shown in figure 3) was created using Revit. The initial planning is also provided by the game, the two houses share all the resources, so any disruption in the schedule of the first house will affect the second one as presented in figure 4.

4.2 Logistics plans of the construction site

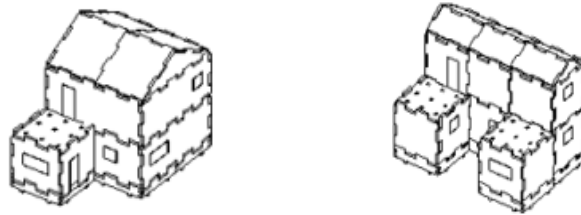


Fig. 3. 3D models of house (A on the left, D on the right)

In this case study, three organizational scenarios, related to the construction industry practices, are considered:

- **Scenario 1 - Ordering all materials at the beginning of the construction project:** This approach is one of the earliest approaches to logistics planning. No information is needed, and all materials required for the project are ordered and delivered to the site before the beginning of the project (figure 5, scenario 1). In this case, the information regarding the work progress might not be of a considerable benefit regarding the storage cost. This type of organization can still be found in small construction projects.
- **Scenario 2 - Ordering materials by batches:** In this approach, the materials are ordered when needed, considering the delivery delay that may occur (figure 5, scenario 2). Normally, the site manager does a routine check-up to track the work progress every two or three weeks before confirming the material order. The information is being utilized for reducing the total cost of the project. Unfortunately, due to infrequent extraction, the information can be outdated, and some extra storage cost may result.

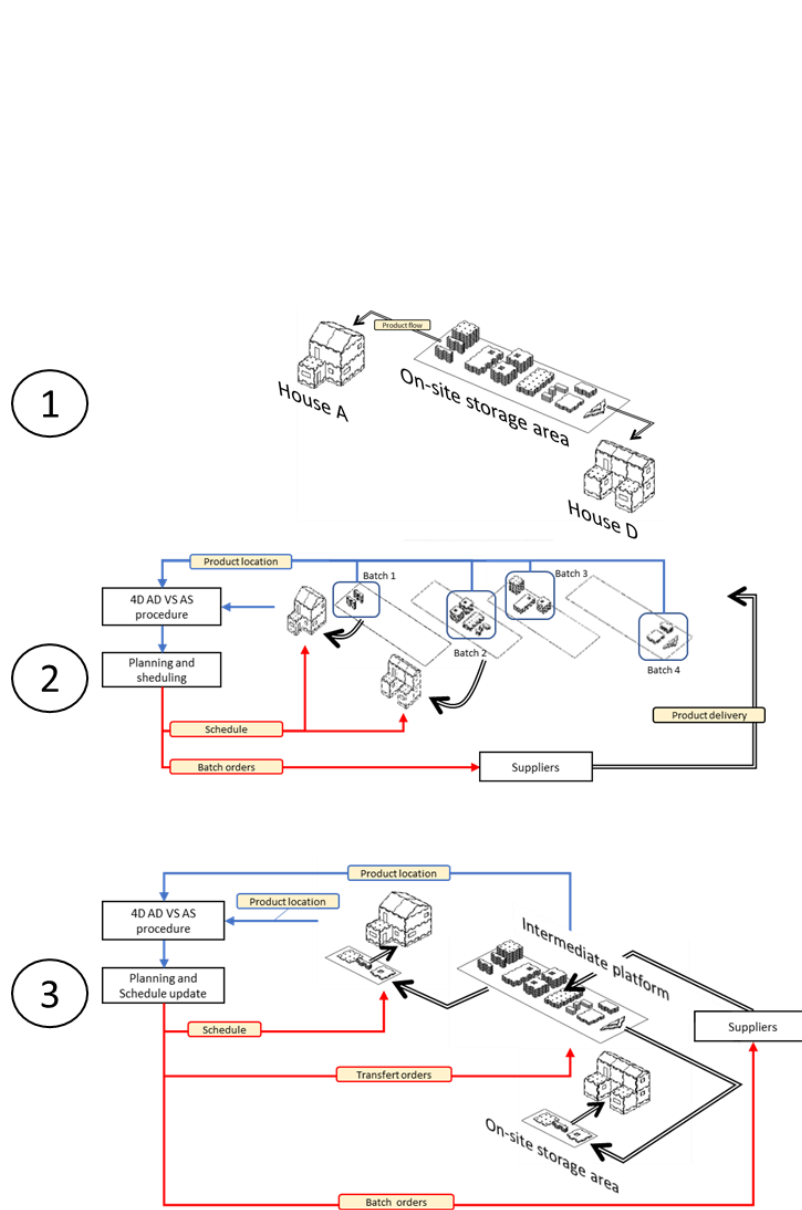


Fig. 5. Representation of the three scenarios with their level and frequency information required

5.1 Results and discussions

For a better overview, the simulation results of the three construction organisations were summarized as total cost with and without information coming from IP. The synchro 4D tool was used to simulate those different scenarios and calculate the associated total cost based the equipment, storage, material and human resources costs. Delay penalties were not taken into account.

The first graph shown in figure 7 represents the total cost of the three organizations without implementing RT-monitoring of the IP, compared to C_{Y_i} defined as the sum of all the Y_i delays in the 4D AB BIM. The first point of each curve (associated to a zero C_{Y_i}) represents the 4D AD BIM (perfect schedule). It is thus a reference cost for each

scenario. The following points represent the costs associated with the 4D AB BIM computed during the simulations.

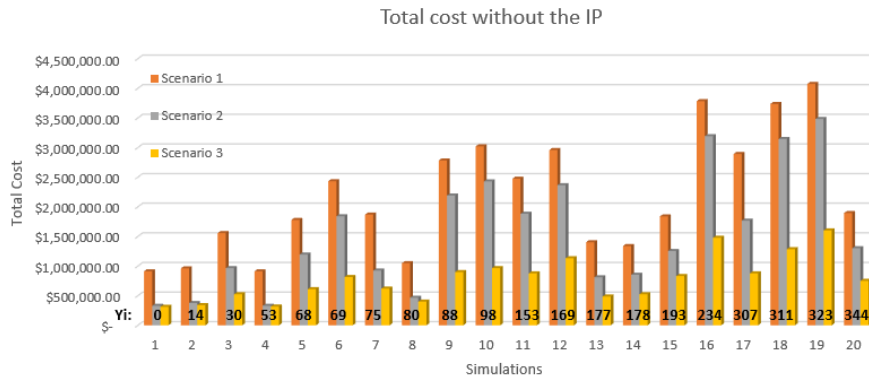


Fig. 6. Variation of the total cost of the three organizations function of the cumulative delay without the IP

The highest cost belongs to the simulation number 19 with a C_{Y_i} of 323 for the first organization the highest cost was \$ 4,073,669.00 compared to \$ 911,267.00 for the 4D AD BIM which is an equivalent of 300% increase, for the second organization we have an increase of almost 900%, whereas for the third one we have of increase of a little over one million dollars in the total cost corresponding to a little under 300% increase. We can notice that the highest cost doesn't necessarily belong to the highest C_{Y_i} , that is due to the fact that the storage cost doesn't only depend on the delay duration but on the occurrence instance as well.

The second graph presented in figure 8 shows the effect of the implementation of the IP. The biggest impact is on the second and the third organizations where the storage cost becomes independent from the delay, resulting in a stable total cost curve, which makes sense since the information availability is crucial in those organizations. As a result, every delay is thus detected the moment it occurs. Therefore, it is easier to determine the good moment to order the next batch and thus to minimize the time spent in stocks. The third organization is slightly more improved in terms of cost, given the fact that there no more need for preserving a worker for the reporting of the site situation daily. It is obvious that the first organization does not benefit from the IP implementation since the cost here is independent from the information, the materials being already in stock, the knowledge of the delay occurrences will have no effect on the storage cost. However, it might be interesting to benefit from the information for replanning purposes to reduce the lead time.

With the implementation of the IP, we can notice immediately that for the second and the third organizations, the cost of the 4D AB stays very close to the cost of the 4D AD BIM which proves the benefit of implementing the IP, however for the first organization the peak value remains the same.

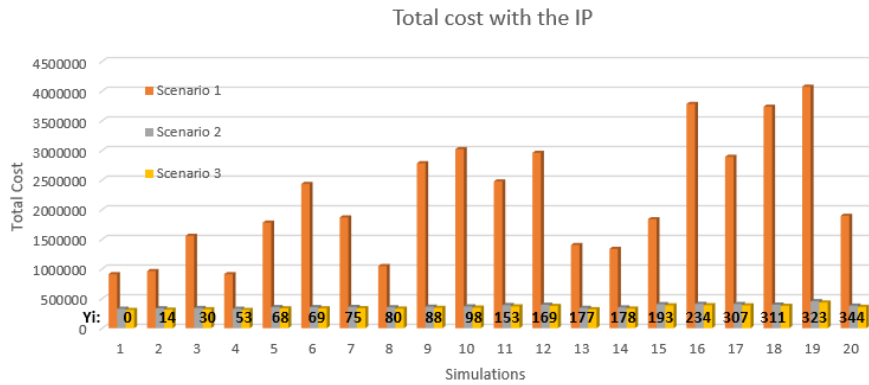


Fig. 7. Variation of the total cost of the three organizations function of the cumulative delay with the IP

6 CONCLUSIONS AND PERSPECTIVES

This paper presented a case study dealing with work progress monitoring, based on the constant flow of information acquired from the communicating materials during the building lifecycle. A 4D AB BIM is created and compared to the 4D AD BIM for early detection of any disturbance in the schedule. As a result, this new method ensures the self-monitoring of the site and does not require any surveying activities. According to simulations this approach could improve the total cost depending on the construction site logistics employed. Indeed, costs are reduced by 76% and 55% for the second and third organization respectively, compared to the traditional pull system. The highest impact is on the storage cost where it is reduced by 93% and 86% for the second and third organization respectively. By using the IP, the information is communicated at every instance and the storage time is significantly reduced.

This work isn't finished yet and there are some uncertainties regarding the information quality obtained from the IP that requires further studies. Concerning the lead time, it was not discussed much in this paper even though it is one of the most important factors. It would then be interesting in the future to validate the ability of using the information for rescheduling purposes in an attempt to reduce the lead time.

7 ACKNOWLEDGMENTS

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