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BIM, Augmented and Virtual Reality empowering Lean Construction Management: a project simulation game

Patrick Dallasega[a], Andrea Revolti[a], Philipp Christopher Sauer[a], Felix Schulze[a], Erwin Rauch[a,]*

[a]*Free University of Bozen-Bolzano, Faculty of Science and Technology, Industrial Engineering and Automation (IEA), Bozen Bolzano, Italy*

Abstract

During the last decades, Lean Management methodologies established in the manufacturing environment have been applied and adapted to the construction industry under the term "Lean Construction". Currently, concepts and technologies from Industry 4.0 are mainly transforming the manufacturing industry and only few applications have been implemented to construction and its connected supply chains. This paper shows how new technologies like Building Information Modeling connected with Virtual and Augmented Reality could empower Lean Construction methodologies to increase efficiency during the building execution process. The approach was tested by using the project simulation game Villego® with students from the course "Project Management" of the master degree LM-33 "Industrial Mechanical Engineering" of the Free University of Bozen-Bolzano.

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Keywords: Virtual Reality; Augmented Reality; Building Information Modeling; business simulation game; learning factory

1. Introduction

The adaptation of lean manufacturing principles to the building industry is called "Lean Construction" [1]. Research in this area has been done since the 1990s. The Last Planner® System (LPS) is one of the most important tools that have been developed within the Lean Construction area [2]. It was developed to improve the reliability of

* Corresponding author. Tel.: +39-0471-017111.
E-mail address: erwin.rauch@unibz.it

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construction schedules by introducing several scheduling phases that are to be defined in collaboration. Today, Industry 4.0 is changing the manufacturing industry by increasing digitization and automation as well as creating digital value chains enabling communication between products, their environment and business partners [3]. Even in construction, Industry 4.0 technologies are slowly but strongly changing this industry [4]. Building Information Modeling (BIM) can be considered as the central and most developed technology for the digitalization of the construction industry. Other technologies like Augmented Reality (AR) and Virtual Reality (VR) have not been fully exploited in construction [4].

This paper shows how new Industry 4.0 technologies could empower the LPS by using the Villego® simulation tool. Villego® is a haptic simulation game used to teach students as well as professionals how to use the LPS [5]. It is composed of two rounds, where in the first round a small Lego house is built by using the conventional construction management approach. In the second round, the Lego house is erected by using the LPS. In this paper, special emphasis is set on showing the effects that new technologies have on the LPS. Specifically, BIM connected with VR and AR as well as a webcam simulating the measurement of the construction progress in real-time were tested. The simulation game was applied during the course Project Management of the academic year 2019-2020 with students from the master degree LM-33 Industrial Mechanical Engineering of the Free University of Bozen-Bolzano in Italy.

2. Basic concepts and background of the study

The LPS [2] has been introduced to improve performance in construction process execution by supporting it with reliable mechanisms for scheduling. The methodology introduces several scheduling phases that are defined in collaboration among the project participants. i) The master schedule depicts the main project phases and milestones covering the entire project duration. ii) The phase schedule further details the master schedule by showing explicitly the hand-offs between the trades involved in a phase. iii) The lookahead plan schedules the activities to be performed within the next four to six weeks with the aim to remove potential constraints that hinder the execution of tasks. iv) The weekly work plan is negotiated between the different foremen involved with the aim to define a feasible plan and commit to its execution. The LPS encompasses also a monitoring phase to analyze planning failures and initiate a continuous improvement process. Therefore, the Percent Plan Complete (PPC) indicator is computed as the ratio between the number of activities completed and the number of activities scheduled in a specific week [2]. When a scheduled task had not been completed, a so-called Reason for Non Completion (RNC) must be provided, which is analyzed by the foremen involved to understand its causes and to apply improvement actions.

BIM is one of the main approaches enabling the digitalization of construction projects [6]. BIM has a great potential for sharing and visualizing information as well as considering changes in design and during execution [7]. In fact, information is centrally stored in the model, which allows it to be shared transparently to the stakeholders [8]. According to (Alizadehsalehi and Yitmen 2016) [9], “BIM can serve as a powerful baseline for progress tracking and for the visualization of discrepancies”. In fact, because of its powerful ability to map the physical building into a digital environment BIM holds potential for the visualization of the construction progress because it can visualize and express information more intuitively [10].

New technologies are also emerging as innovative teaching tools in learning factories. Reining et al. 2019 [11], proposed the use of recorded footage to increase learning and discussion within student working groups as well as to identify competences addressed in learning factories. Adam et al. 2019 [12], discussed how Information Technology (IT) can be integrated into a lean basic training module within a traditional lean learning factory environment. Juraschek et al. 2018 [13] gave an overview of potential applications of Mixed Reality (MR) in learning factories to enhance knowledge and skills of future factory operators.

3. Method

The Villego® simulation was applied during the course Project Management of the academic year 2019-2020 with students from the master degree LM-33 Industrial Mechanical Engineering of the Free University of Bozen-Bolzano in Italy. Seventeen students participated in the simulation with a duration of four hours. The allocated roles of the project simulation game were as follows: one construction manager and one assistant, three data collectors and two students for every subcontractor, grey, green, blue, white, red and yellow. The construction manager and assistant were responsible to coordinate the different subcontractors for an efficient assembly of the Lego house on-site. As a rule, prefabrication was not allowed, which meant that Lego bricks could only be assembled directly on-site. The simulation was composed of six subcontractors, according to the colors of the Lego bricks (e.g., subcontractor grey is responsible to lay the foundation; subcontractor green is responsible to assemble windows and doors). The construction duration was measured and displayed on three screens. Every 10 seconds an acoustic signal appeared that mimicked one day in the real construction environment. As such, one minute represented a week with six working days. The construction site was represented by using a green plate (Fig. 3b) and the space was limited by means of a red-white adhesive tape on the floor. The data collectors were asked to sit on-site and to collect the following types of information (at every acoustic signal). i) The total construction time. ii) The specific trades that were present on-site. This information was aggregated into the KPI "Subcontractor time on-site" (Table 1). iii) The number of safety breaches, where the following rules were applied. Only two people were allowed on-site at the same time. If subcontractors stayed on-site, they needed to wear personal protective equipment by means of a shield cap. iv) The amount of wasted material, where Lego bricks that were not correctly assembled, had to be put into the red container (Fig. 1a). v) The number of reused material in terms of bricks placed and then replaced counted as a further penalty cost (see Table 1).

In the following paragraphs, the processes of the first and second round are explained in detail. Before the start of the first and second round, the group was allowed to study the assembly plans and working instructions for 20 minutes. In *Round 1*, the Push production management system based on the Critical Path Method (CPM) was applied. Here, the construction manager and his assistant had to call the different subcontractors to perform their work on-site based on a traditional construction schedule elaborated with the CPM and represented as a Gantt chart. In *Round 2*, the LPS and Industry 4.0 technologies were applied. The composition of the Lego house was changed in the second round to avoid a distortion of the results through learning curve effects. Innovative technologies from the Smart Mini Factory laboratory [14] were used. These were Oculus for VR, the Microsoft HoloLens for AR, a hard rugged tablet showing the BIM model of the Lego house as well as a webcam recording and visualizing the construction progress in real-time on the screens of the lecture hall. To keep the framework conditions the same as in the first round, the participants were allowed to study the drawings and working plans for 20 minutes. In addition, every subcontractor was allowed to navigate the digital building model in VR by using the Oculus for not more than 3 minutes (Fig. 2a). Opposed to the first round, the phase scheduling as part of the LPS, was applied. Here, the students were asked to plan collaboratively the process in a backwards way by putting sticky notes on specific forms on the wall of the lecture hall (Fig. 1b). Every sticky note displayed the specific task, its duration and the needed predecessors. As a further improvement, the weekly work plan (as part of the LPS) was applied. Here, every week (60 secs.) a specific form called "commitment planning" had to be filled out indicating the specific tasks that were collaboratively planned to be performed for the following week. In the second round every week (60 secs.) the simulation was stopped and the number of completed tasks was assessed. If tasks were not completed, a specific "Reason for Not Completion" had to be indicated with the aim to initiate a continuous improvement process among the participating students. As a further refinement of the second round, the construction manager was wearing the smart glass Microsoft HoloLens to project the digital Lego house in AR (Fig. 2b). This was an important assistance to perform a continuous target-performance comparison with the aim to help the subcontractors on-site in placing the Lego bricks correctly. Moreover, in the course of the second round, a webcam was placed on-site with the objective to visualize the progress of the Lego house in real-time on the three screens of the lecture hall (Fig. 3a). In addition, a rugged tablet showing the BIM model of the Lego house was placed on-site. In this case, if subcontractors had difficulties in understanding where to place the different Lego bricks, the BIM model on the rugged tablet could be used.

4. Results

Table 1 lists the Key Performance Indicators (KPIs) that were measured in the first and second round. The construction time could be drastically reduced (almost to one third). Interestingly, the subcontractor time on-site was decreased from 91 to 37 days (1 day = 10 seconds) while at the same time the productivity on-site was increased (nearly tripled). In other words, this means that subcontractors were less on-site but much more productive or focused to the value adding work compared to the first round. Similarly, the idle time (no activity) on-site decreased from 19 to 2 days, which can be attributed to the collaborative planning process and as such, the improved coordination by the LPS. Considering the quality aspect, errors in the finished building could be eliminated, material was less reused as well as less wasted. Finally, yet importantly, the number of safety penalties could be decreased to less than half compared to the first round.

Table 1. Key Performance Indicators of the first and second round.

	Round 1	Round 2
Construction time [min]	16	5:30
Productivity [elements/min]	6.38	18.55
Subcontractor time on site [10 seconds]	91	37
No activity on-site [10 seconds]	19	2
Errors in finished building [#number]	1	0
Safety penalties [#number]	12	5
Penalty for reuse of material [#number]	5	4
Wasted material [#number]	5	2

The following section discusses the impact of the LPS as well as the four technologies BIM, VR, AR and the webcam used in the second round. To highlight the contribution of the LPS and the different technologies the participating students were interviewed. Figure 1 visualizes the first round of the simulation game (on the left) and the application of the LPS (on the right). Both the KPIs as well as the feedback from the students underline the positive impact of the LPS. The students reported an improved confidence regarding their tasks and especially in the coordination of their work. This is reflected in the lowered number of safety breaches, errors, wastes and reuses of material, but also in the much lower construction time. According to the students, the main drivers of these enhancements were the improved clarity of the planning approach that defined a clear sequence of actions as well as the support by means of colored instead of black and white construction plans. These benefits enabled a better orientation of the students both in terms of timing and placing the Legos on the right spot. In effect, the mentioned benefits of the planning approach resulted in a much-improved productivity rate. Figure 2a visualizes the application of VR by using the Oculus smart glass. Here, every trade leader was allowed to study the Lego house of the second round by navigating the digital building model. The feedback on the AR and VR was quite mixed. While the VR was found to be too complicated to handle for people without prior training, the AR was perceived as very useful. As shown in Figure 2b the construction manager used the AR during the entire construction process in the second round. This was evaluated as very supportive for the determination of the correct positioning of the Legos, as it could be verified in real-time. In effect, this was seen as a driver of workers' confidence that reduced hesitation and improved productivity. For future improvement of the digital tools, the students reported on their experience and suggested three changes. First, the possibility to switch layer by layer of the BIM model in the AR application was requested. Second, a time dimension could be integrated in the BIM model, such as a time dependent development of the physical building. Both would allow an easier comparison between the correctness and the timeliness of layers built as well as the layers designed. The third feedback was to put the BIM model on a similar background as the actual Lego house, to allow the possibility to overlay it facilitating a quick and easy recognition of individual building elements.

a) b)

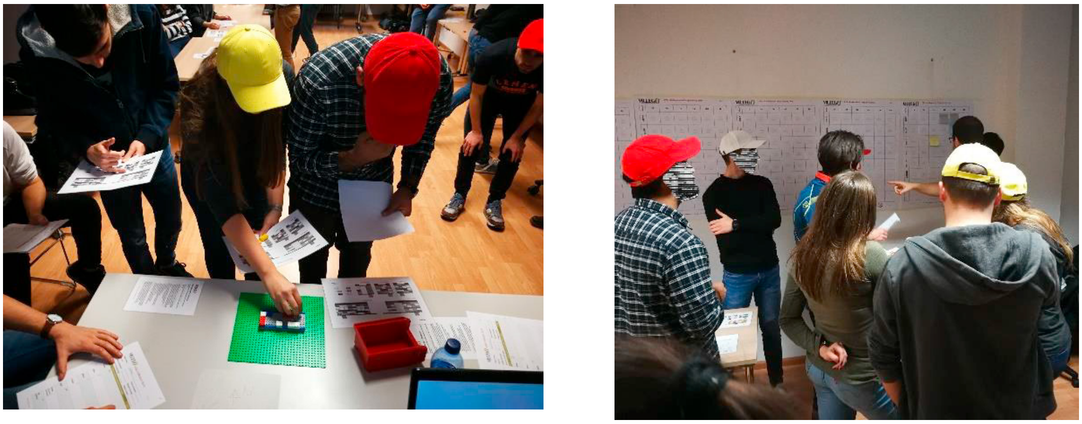

Fig. 1. (a) First round of the simulation game; (b) second round of the simulation game.

a) b)

Fig. 2. Application of Virtual Reality (a) and Augmented Reality (b) in the second round.

a) b)

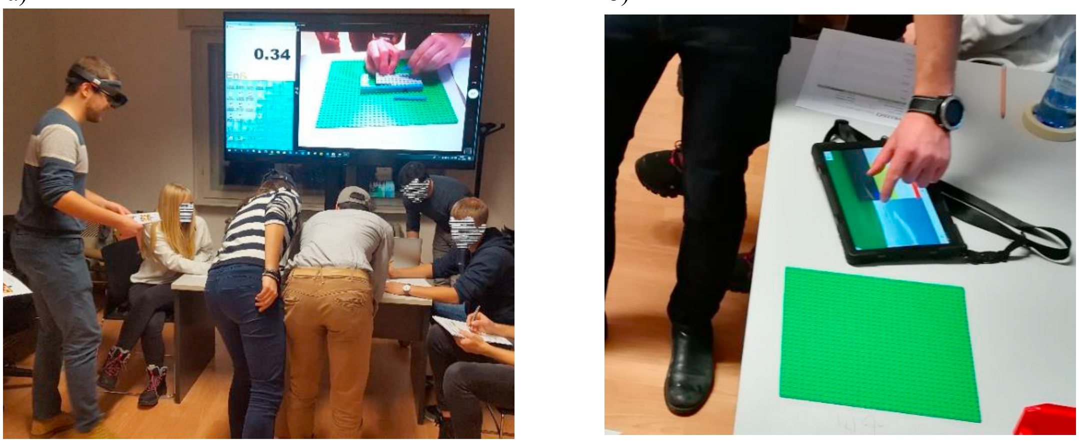

Fig. 3. Application of webcam for progress measurement (a) and BIM on-site (b) in the second round.

Figure 3 shows the application of the webcam for real-time progress measurement as well as the tablet displaying the BIM model on-site. The webcam was broadcasted on three screens across the room, which simulated a streaming of the construction progress to the single partners of the supply chain. This was perceived as useful for an intuitive orientation of the students regarding the progress and thus their next actions on-site. The students consequently reported less idle-times and less stress, as they could verify the progress themselves at all times.

The tablet however, was used less than expected, which maybe is due to its redundancy to the colored building plans that the students studied before coming on-site. Moreover, the tablet was redundant to the information given by the construction manager who used AR with basically the same information.

4. Conclusion

The paper shows how innovative Industry 4.0 technologies, like Building Information Modeling (BIM), Virtual Reality (VR) and Augmented Reality (AR) could be used to support Lean Construction. The approach was tested by the Villego® simulation with students from the master degree LM-33 Industrial Mechanical Engineering of the Free University of Bozen-Bolzano in Italy. Overall, these technologies demonstrated to have a positive impact on improving Key Performance Indicators (KPIs) like overall construction time, less idle time on-site an improved level of quality as well as sustainability in terms of less wasted material. While AR by using the Microsoft HoloLens was felt to be very intuitive, the usage of VR by means of the Oculus device was perceived to be very challenging. Overall, the technologies showed to improve the spatial-temporal orientation of the project participants.

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