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LEVERAGING BIM AND MIXED REALITY TO ACTUALIZE LEAN CONSTRUCTION

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ABSTRACT

Lean construction is made of principles, measures and methods that aim at maximizing process efficiency. Several tools have been developed to minimize waste, maximize customer value, improve the conduction of processes, and pursue other sub-objectives in construction. This effort is becoming more and more important due to the rising construction project size and variety, displacement of resources in diverse geographic locations, high-performance pressure.

This paper reports the development and on-site tests in a real-life demonstrator of two management tools, which apply some principles of lean construction management at the design and delivery phases. The first one takes advantage of the integration between BIM and mixed reality, having the final aim of improving collaboration and communication among the actors involved. The second one exploits BIM modelling and search algorithms within a process-based management platform, in order to facilitate short-cycle planning and distributed decision-making in the production process.

Both tools have been tested in the case of a building renovation project. The results show that they can improve communication efficiency, reduce rework, speed up work monitoring, control and supervising in construction management, and that they can address several of Liker's lean principles, as classified by the 4P model.

KEYWORDS

Lean construction, collaboration, BIM, mixed reality, process.

INTRODUCTION

Many actors participate in the administrative and operational levels of the building business, which makes it a complex business area. The construction supply chain often involves a number of participants even in small construction projects. As a consequence, complexity mainly arises at the interfaces between sub-processes (Dirnberger, 2008; Kolberg et al., 2017) and it has become a critical topic in the field of construction project management (He et al., 2015; Brady et al., 2018). Although there is no consensus on the exact definition of complexity (Ma et al., 2020; Gu et al., 2022), construction processes can be considered to be some of the most complex ventures across all industries, even because the construction industry has experienced speedy progress in projects of rising size and variety. Large scales, sophisticated technical processes, long lead times, huge numbers of people involved, diverse geographic locations, and high-performance pressures make these projects even more complex (Mirza et al., 2017; Zegarra et al., 2019). The developers of the Management 3.0 approach provided several basic

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recommendations (Appelo, 2011): to address complexity with complexity; to use a diversity of models; to assume dependence on context; to anticipate, adapt and explore; to develop models in collaboration; to manage changes. Nowadays, dealing with complexity has never been more important and it requires that an organization is connected with its environment and can adequately react to its changes (Frahm & Roll, 2022).

In such a scenario, most of the principles, measures and methods of planning, designing and controlling applied by lean construction thinking can help the construction industry to deal with external factors that characterize the economic framework, such as high demand (and increasingly scarce resources), low price levels, an increasing competition and constraints determined by political and normative factors. Furthermore, the demand for renewable energies, resource conservation, and rising qualitative standards asks for the adoption of new methods that are able to improve the overall process efficiency, which is one of the main objectives of lean construction (Fiedler, 2018; Neve et al., 2021). Lean construction pursues important goals such as maximizing customer value, continuous improvement of processes, elimination of waste, application of flow and pull principles (Seed, 2015). Waste can be found in many interfaces between processes, due to insufficient communication and collaborative work between teams (e.g. lack of operational management, deployed international teams), but waste can also be generated by low price levels in budgeting and legal proceedings against projects. During on-site activities and in case of a tight work schedule (e.g. parallelization of activities), issues can arise because of mutual obstructions of trades, high costs of rectifying defects, increased need for control by site managers. As a result, projects often are not able to adhere to deadlines (Frahm & Roll, 2022).

In this paper, lessons learned from a three-year EU-funded project entitled "ENCORE – ENergy aware BIM Cloud Platform in a COst-effective Building REnovation Context" will be presented. More specifically, a couple of web services that can help achieve a possible implementation of lean construction methods will be showcased. The first one integrates Mixed Reality (MR) tools to show how they can be used within construction projects to enable collaboration between the design team and on-site users to identify errors/omissions quickly and correctly (Surendhra Babu & Nayath Babu, 2018). This approach makes the decision-making process at the design phase reliable and efficient, because it avoids time delays due to re-works, thanks to an on-site acquisition of information about the designed model and the opportunity to do adjustments in an immersive hybrid environment (Orihuela et al., 2019). The second one is a process-oriented planning and control platform, which exploits BIM, advanced computation and visualization to enhance decision-making in work planning, workspace management, coordination and collaboration during work execution, in order to eliminate wastes due to delayed response to the unexpected, blocked space and passages (Singh & Delhi, 2018). Both tools have been enabled by the development of the design model within a Building Information Modelling (BIM) environment. Experimental tests were performed in the specific case of energy renovation of residential buildings.

The technical details of the platforms will be described in the next chapter. Findings from these experimental tests and lessons learned will be reported and discussed right after that. A conclusions section will end the paper.

TECHNICAL DEVELOPMENT

The architecture of the ENCORE platform (CORDIS, 2023) is structured into four layers: (i) data sources; (ii) data capture; (iii) engines; (iv) applications. It is based on micro-services. The "Applications" layer contains that set of services visible to the main end-users. Among them, the MR web service supports the architect in the creation of renovation options for building efficiency improvement, until one of them is selected as the preferred one. The other web service performs process-oriented management of construction works: it accepts the IFC model of the selected renovation option as input and produces the first work plan and a list of spatial clashes between trades as output. Indeed, site managers and planners can use this platform to check whether the site layout has been arranged accurately, to control the actual work progress, and to update the work plan.

COLLABORATION PLATFORM AT THE DESIGN PHASE

The final purpose of the MR web service was to facilitate the assessment of alternative options for the energy renovation of buildings. In this phase, quite close cooperation between the architect and a few technical experts may be required. Indeed, the feasibility and constructability of renovation options must be checked by means of on-site surveys, due to the limitations and technical constraints caused by the layout and components of the existing building. Thanks to the integration between MR and BIM modelling, the on-site verification can be performed more efficiently, mainly because of the immersive visualization of renovation option models and because of the enhanced collaboration and communication between the architect and involved experts.

The workflow enabled by this platform is sketched in Figure 1. First, the architect is supposed to develop alternative renovation options in the form of BIM models. Every option must be assessed in terms of energy performance. Then, the architect is expected to single out that subset of studies that must be verified by means of an on-site survey, due to constructability issues. Once an expert gets on-site to perform such an assessment, they will enrich every candidate option with information regarding their expert opinion. Eventually, the architect is able to combine all the available information (e.g. feedback received from experts, information embedded in the IFC model) until they can make a decision and select the preferred solution that will be built.

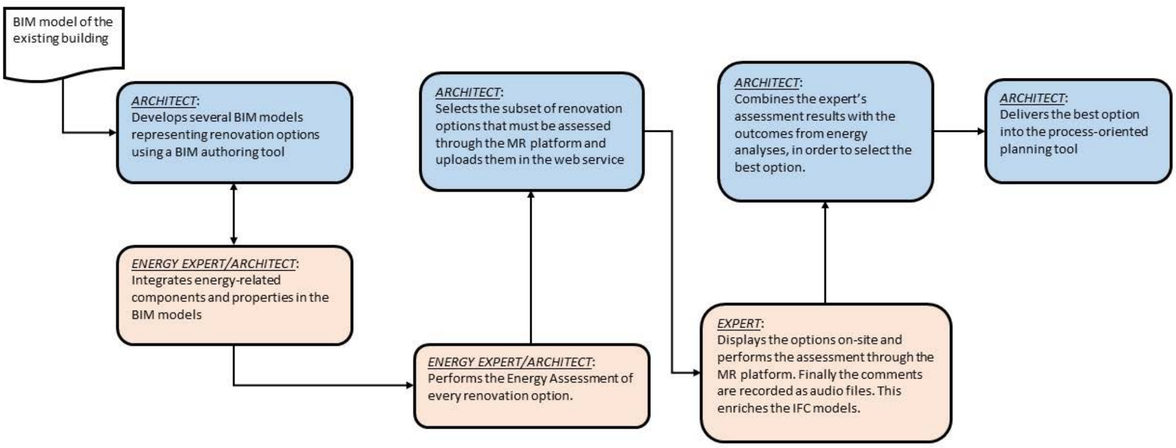


Figure 1: Workflow enabled by the collaboration platform

The platform enables seamless communication and coordination according to the cognitive interpretation of holonic management systems (HMS), which is depicted in Figure 2, and which provides greater agility and increased robustness against disturbances as compared to centralized systems (Mella, 2009). In this view, holons are defined as cognitive units of holarchies that are made of one or more agents and can dynamically reconfigure themselves into new holarchies. As long as this approach is transferred to the case at hand, the holon representing the on-site expert can either make individual decisions or can participate in the collective decision. In the latter case, they give birth to the multi-agent system in a distributed collaborative framework, made up of the on-site expert and members of the design team, thanks to the MR interface and the web service (Figure 2). This avoids requiring centralized decisions only (Valckenaers and Van Brussel, 2016; Derigent et al., 2020).

To this purpose, renovation options are stored in the Encore platform by designers as IFC files and by means of a dedicated Graphical User Interface or GUI (Carbonari et al., 2022). They can be received by the platform through a Restful API. Then, they are passed through an IFC2GLTF translator that converts them into the GLTF 2.0 specification. In this step, a JSON file that contains data and relationships other than geometrical and metadata is created, too. This set of information will be used to produce the game scene by the expert's MR App. In fact, as soon as an expert gets on-site, they will execute the MR app that was developed in Unity 3D 2019 environment with Mixed Reality Toolkit, compiled and deployed in the Hololens by Visual Studio 2019. Once the App has been started and authentication accomplished, the MR App invokes an URL of the App Restful API returning the list of projects to be assessed. Once one of the projects has been selected, this triggers a GET request to fetch the GLTF file ready to be rendered in the game scene of the MR App, together with complementary information included in the JSON file. The model is ready to be aligned by means of visual tags. First, the expert gazes at a tag placed on-site. Then, the MR app sends the serial number to the web server, which localizes the same element in the IFC model. As soon as at least two tags have been scanned, an internal routine aligns the model around the expert. Here is when the immersive experience starts. The user can navigate the model on-site and upload their remarks and suggestions onto the web service, recording voice comments as audio files linked to relevant components of the IFC model. The architect can access the service and go through annotations produced in the assessment until they reach the final decision.

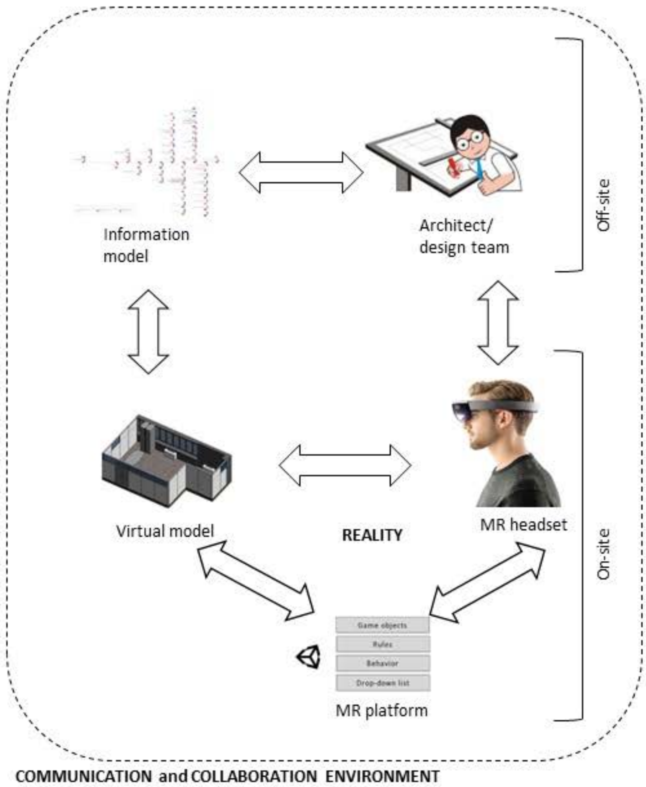


Figure 2: Conceptual diagram of the collaboration platform

PROCESS-ORIENTED PLATFORM TO MANAGE THE EXECUTION OF WORKS

The second web service consists in a proactive, partially automated, human-machine cooperation platform, that was based on the operative interpretation of the Holonic Management System (HMS) architecture, which is made of self-organizing modules (Mella, 2009). Its implementation followed the PROSA (Product-Resource-Order-Staff Architecture) reference architecture (Valckenaers & Van Brussel, 2016), because of its capabilities of mediating between low-level and high-level decisions while sticking to a shared objective.

Basically, this process-oriented platform adopts a process-based representation and an ontology that facilitates the creation of the initial work plan and its regular update during the execution of renovation works (Figure 3). It requires that the renovation project input is provided as a BIM model, including the current state, the demolish phase and the renovation phase. Then, the planner can cluster the components into construction deliverables and can define any applicable milestones (Messi et al., 2021). This web service helps the planner to retrieve information about the BIM product and the applicable price analysis and to bind this information with the construction processes represented in Business Process Modelling Notation (BPMN). As a result, every construction deliverable will be associated with the corresponding process and required resource skills (embedded in the resource/cost analysis source repository valid for the selected price list). Then, a stigmergic planning algorithm works out a plausible work plan labelled as the baseline. This approach facilitates even re-planning during the control phase, once data about work progress are collected from the job site. Finally, an external visualization and spatial simulation tool to check spatial conflicts were developed, in order to warn whether two trades would work in overlapping workspaces.

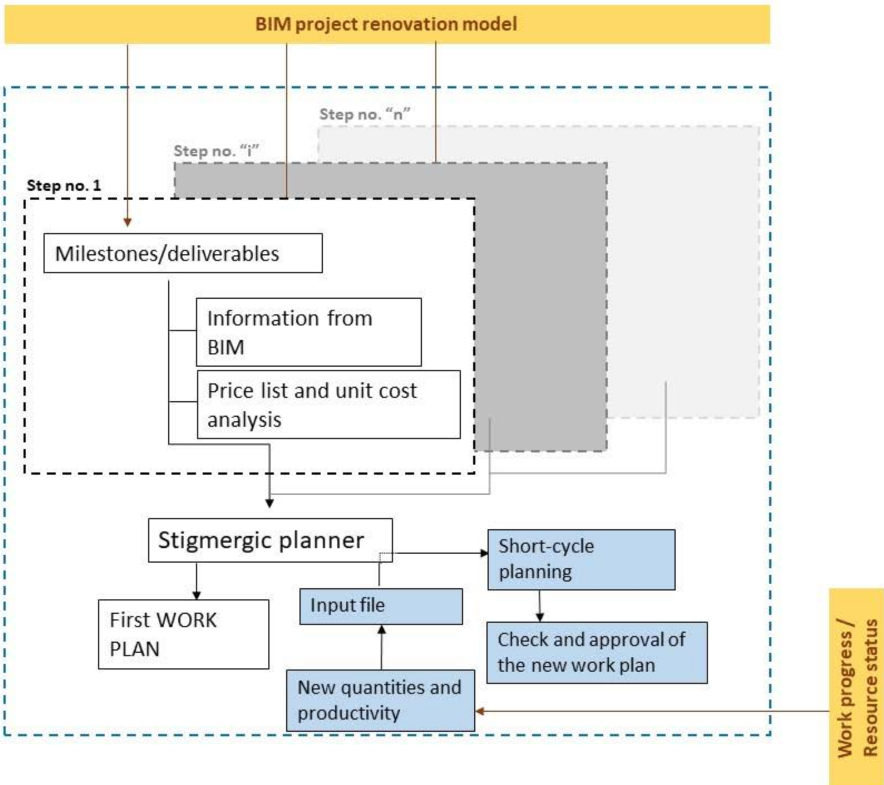


Figure 3: Conceptual diagram of the process-oriented platform

The interaction with the platform is managed through a Web GUI that integrates the sub-services (Figure 4). Once the login is successful, a member of the design team can import two IFC2x3 Coordination View files, which is one of the MVD types provided by BuildingSmart and available as a function in all certified BIM platforms. They are the existing and the to-be-renovated design models of the building, respectively. They can be compared using an in-built function that recalls one of the "IFC Web server" functions to compute differences and work out the list of components to be demolished and the list of components to be built, eventually stored as an editable CSV file.

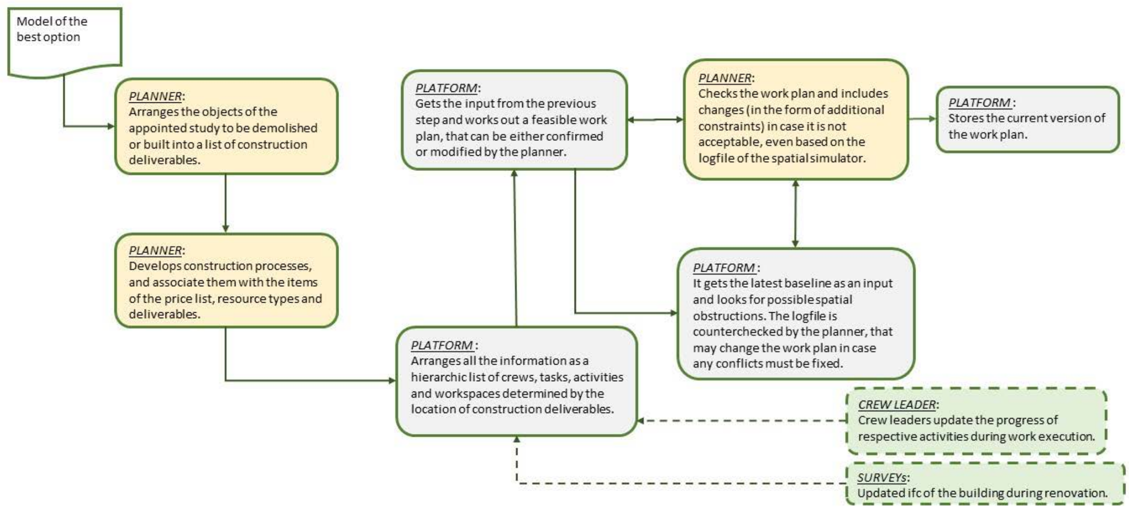


Figure 4: Workflow enabled by the process-oriented platform

The GUI allows the user to edit such a CSV file and generate the list of deliverables. It consists of the rearrangement of those components in order to put together sets of components that will be executed in the same workspace and by the same crew, hence it can be described by one process. A built-in BPMN editor facilitates the creation of BPMN models, either generated from scratch or imported from previous sessions. Thanks to its formal specification in XML, every activity in these processes is linked with the deliverables and the corresponding item of the applicable price list, called by invoking a Python web service. It interacts with the main web service by means of an API REST. Crews are automatically imported from the price list and the analyses of unit costs. Bills of quantities and efforts of crews are generated automatically using the size and other attributes included in the MVDs and deliverable list. They can be counter-checked by the user. All this information is accommodated in a JSON file that is the input of the stigmergic search algorithm, which is started by invoking a Matlab™ simulation environment (Naticchia et al., 2019) and produces work plans. These processes are supported by a multi-model DB developed in ArangoDB (ArangoDB, 2020). The resulting work plan can be imported into an external service developed within Unity3D™, along with the IFC model of the building. Its engine displays workplaces and, then, it checks for spatial conflicts, that is workspaces that may be occupied by different trades at the same time. The list of conflicts can be checked and fixed by the site manager. Finally, a web interface was set up to type in percentage values of work progress. These figures are transferred to the web server by means of a REST API. They overwrite the quantities included in the JSON input file to the stigmergic planner and trigger the algorithm again, until a new workplan is provided as output. As a result, the on-site cooperation among crews providing progress data, the search algorithm for planning, the construction manager, and the information included in the BIM environment realize a collaboration environment, partially automated, that can be regularly and often implemented during work execution.

LESSONS LEARNED

RESULTS OF EXPERIMENTAL TESTS

The tests carried out in the demonstrator building in Caceres showcased the functionalities of the MR service and the main advantages derived from its adoption. The collaboration environment is hosted by a web service in which designers and experts can upload and share design options. As shown in Figure 5-a, several studies or solutions can be associated with a project. They are uploaded by the architect. Once the experts have downloaded those files in their headset on-site, and have accomplished the on-site survey, they are expected to enrich the model with remarks, that are linked with the relevant components of the building and can be retrieved and listened to by the architect at any time. The web page in Figure 5-b shows that as soon as a comment is played, the web service highlights in colour the component to which the comment is attached, thus facilitating the exchange of relevant information.

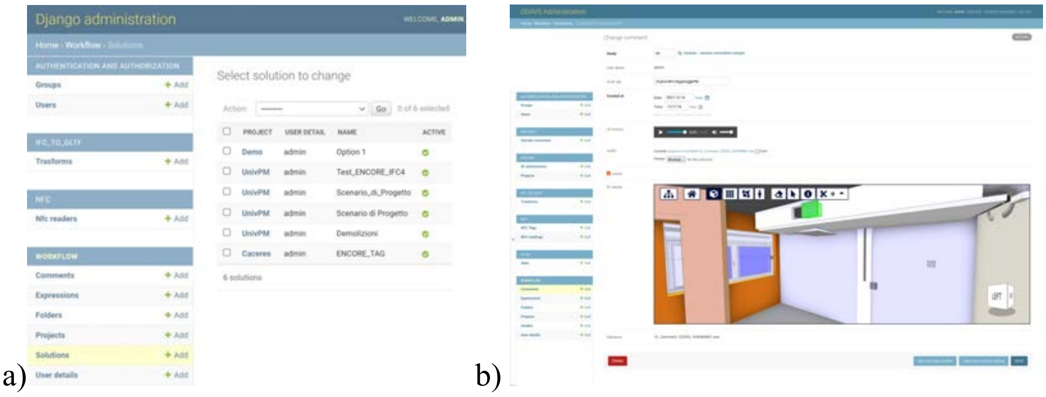


Figure 5: Collaboration environment supporting the evaluation of renovation options

The enrichment deriving from the generation of comments and remarks was made possible by the combined visualization of the physical environment and the virtual model (Figure 6-a). In this Figure the pointer of the user that queries the properties of a vertical pipe is well visible. Figure 6-b depicts an on-site user in the process of interacting with the mixed environment and reaching out a physical component. They can measure the size of a component, can touch and sense the surface of a component to infer the material that it is made of. While interacting with the physical part and wearing the MR headset, the latter does not interfere with these actions. Rather, the MR headset facilitates such navigation and the gathering of additional information. The first-person view of a recording session is shown in Figure 6-c, where the virtual menu handled by the expert is located at the forefront. The recorded remark will be saved in the web service and can be retrieved as shown in Figure 5-b. Additional pictures and videos of these tests are available in a repository authored by Carbonari and Vaccarini (2022).

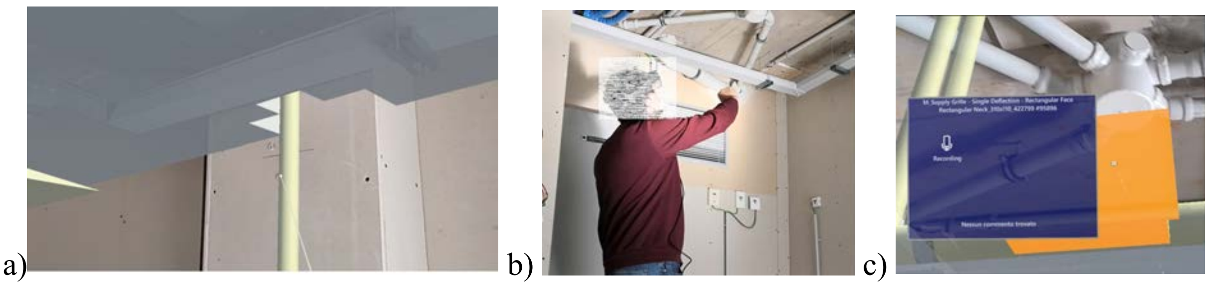
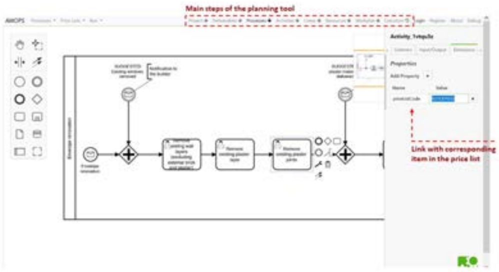
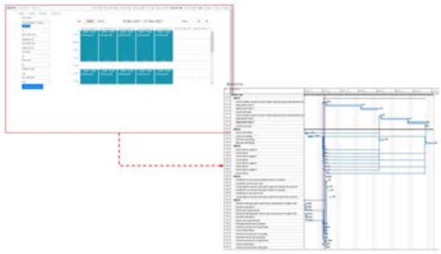


Figure 6: First-person view of an operator mixing information of the current and renovated building (a); use of the platform during the tests (b) and virtual menu to record a comment (c)

Also, the web page of the process-oriented platform that enabled the development of the BPMN processes to manage the renovation works to be executed in the demonstration building located in Caceres is shown in Figure 7-a. According to what reported in the previous section, every node of the process represents a type of activity, which is later instantiated by the system in order to generate the input for the planning algorithm. In other words and as an example, the node “remove plaster” generalizes the two tasks “removal of plaster on the north facade” and “removal of plaster on the south facade”. These instances will be created by the system thanks to the relationships among these nodes, the items of the price list and the deliverables edited and approved by the planner in the previous step. The last step of the planning process that generates the schedule of renovation works is shown in Figure 7-b, along with the baseline worked out by the system. To sum up, the baseline includes five groups of activities: removal of some components and of the plaster; application of insulation layers and of the new plaster on the facades; installation of temporary structures (e.g. scaffolding); installation of sun shading systems and robotic arms to control window opening; replacement of windows. The same data structure and the stigmergic algorithm applied to work out the baseline will be executed during work progress management, in order to perform a short-cycle replanning. The overall duration of this plan spans from March 12th until April 25th, 2022.





b)

Figure 7: Notation used to model processes (a) and schedule generated by the platform about the renovation works performed in the pilot building (b)

Then, work progress was controlled and plan updates were worked out quite often, as listed in Table 1. At every replanning step listed in this table, work progress was updated and a new work plan was generated by the platform.

Table 1: Re-planning dates during project control

Date	Work progress	Estimate completion date
2022/03/12	Temporary structures are done.	2022/04/25
2022/03/14	Demolitions; envelope insulation (partial).	2022/04/04
2022/03/17	Envelope plaster and insulation; shutters (partial).	2022/03/31
2022/03/21	Shutters; replacement with new windows (partial).	2022/04/04
2022/03/24	Sealing around windows (partial); finish layer (partial).	2022/04/25
2022/03/28	Sealing around windows (partial); finish layer (partial).	2022/03/31
2022/03/31	Renovation works on hold.	2022/04/06
2022/04/07	Installation of shutters (partial).	2022/04/11
2022/04/11	End of renovation works. Construction site dismantled.	-

Work progress was monitored thanks to a web service which could receive percentage values of completion of every single task. The site manager and supervisor may be in charge of gathering such data. The same people can be in charge of changing any relationships among activities and including new constraints whenever applicable, e.g. a supply of windows was late; a precedence between tasks was created due to operational issues. Basically, this is how the platform helps managers to react against disturbances generated by unexpected events occurring during the execution of works. Late deliveries of materials and breaks due to bad weather were the main reasons why the estimated completion date of the project varied so much during the process (see the rightmost column of Table 1). Every time these data had been updated, the planning tool was executed and a new work plan was generated. Then, every work plan was checked using the spatial simulator shown in Figure 8-b. Such a tool displays a coloured box around every workspace; the association between trades and workspaces is listed in the leftmost column in the graphic environment. In case any obstructions were noticed, crew leaders would be asked either to adjust the size of or to move their workspace. In case this action was not determinant, the supervisor or site manager was required to adjust the work plan and fix the issue. In this way, the supervisor was involved in the decision if and only if strictly required.

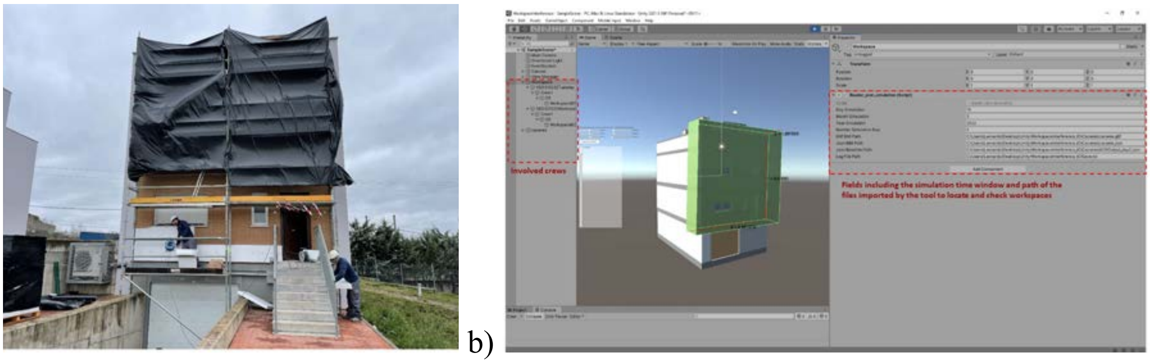


Figure 8: The crews carrying out the execution works on the facades (a) and check of obstructions between trades (b)

DISCUSSION ON LESSONS LEARNED

The volunteers who tested the MR-based platform managed to enrich the BIM model with their opinions, and most of those remarks were available on the platform at the architect's disposal. In particular, 85% of the audio files recorded in the first experimental session and 77% of the audio files recorded in the second experimental session were saved accurately. This is a high percentage if we keep in mind that the volunteers had had no previous experience with the technology. Also, the process-oriented platform supported the creation of the baseline and worked out a new plan on the occasion of each of the eight control milestones of the work progress (Table 1).

Besides these successful quantitative figures, the results of the tests showed that they can address some of the principles underpinning Liker's 4P model (Puram et al., 2021). They are classified into four categories, i.e. philosophy, people and partnership, process, and problem-solving.

The collaboration platform addresses both "process" and "problem-solving" principles. Indeed, it was able to generate a shared environment to be consumed by two types of users in different locations. The first type is the architect and the rest of the design team, which could upload and share information created by experts at any time. The other one is the pool of on-site experts, who could work in an immersive environment and retrieve, edit, or create information enriching the model. These capabilities facilitate the generation of consensus among decision-makers prior to moving forward into the next step and implementing the project. What is more, the information embedded in the virtual model could be combined with the information related to the actual building. The platform allows all of them to organize asynchronously their job. This eliminates waste due to scarce collaboration or difficult communication. In addition, the concurrent assessment of the to-be-renovated design inside the existing building, increased the quality of the assessment and reduced defects in the project. As a result of interviews carried out among the volunteers performing the tests (Carbonari et al., 2022), it came out that the customer/owner could benefit from this platform, because they could have a better understanding of the design and would improve their communication with the design team. Other suggestions concern the extension of the capabilities of the virtual menu in order to increase the possibilities of handling the virtual model, and a more refined selection of the components, so that experts could assess even smaller parts of the project.

The process-oriented platform facilitated the rapid implementation of the execution phase, which is a principle belonging to the "problem-solving category"; it was able to standardize tasks and avoid overproduction, which are classified under the "process" category. In fact, the data model underlying the renovation design models in the IFC files facilitated connection with external sources, such as the price list, and the rearrangement of those data into a format that could be managed by the stigmergic planning tool. Thanks to this approach, the burden of work in charge of the planner got limited and the work plan worked out through computations always minimized the cost function regarding resource usage over time. The second feature is the stigmergic algorithm itself that is able to work out a new plan within a time span in the order of a few seconds. In this case, the combination of BIM and BPMN dramatically speeds up the planning and re-planning process. This figure depends on the number of iterations performed by the search algorithm and by the number of activities. In the case of the demonstrator, which has a limited number of activities, increasing the number of iterations from 10 to 100, would increase simulation times from 3 s up to 29 s. Finally, the integration of the spatial interaction environment as an external tool helped avoid obstructions among trades and helped involve crew leaders at the right time and only when needed, in order to agree on the site layout and the organization required to carry on renovation works.

CONCLUSIONS

Two web services were showcased and evaluated through on-site testing, in order to show how the adoption of a BIM-based work environment coupled with state-of-the-art technologies could realize a lean management approach.

In the first case, mixed reality and BIM models of building renovation projects were combined to create a shared environment inside which many actors could enrich those models with additional information; they could interact with both the physical and the virtual domains; they could cooperate until the selection of the best renovation option was made. The most important benefits brought to the surface by this demonstrator are that communication among the involved actors has been made easier and the quality of the assessment has been enhanced. As a result, the expected collaboration and rework burden will be reduced.

In the case of the process-oriented platform, the combination of modelling techniques to develop process models and the development of BIM project models for the renovation of buildings, allowed the adoption of a planner to speed up the processes for the creation of the baseline. In addition, this technology supported a short-cycle replanning, which realizes a prompt reaction against disturbances generated by external factors and the environment. The BIM and the work plan were imported into a spatial simulator to compute any obstructions between trades that could generate hazards. Several actions in the process were made automatic and did not require manual processing by the planner. Also, decisions could be made at different levels. The adjustment of workplaces to avoid obstructions usually were to be made by crew leaders; however, sometimes a change of relationships between tasks and their start and end dates required a briefing between the supervisor and suppliers. In other words, this approach required the involvement of only the necessary people at every step, with no waste of resource effort. Finally, enhanced visualization of information and models and the continuous availability of data increased operational efficiency.

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