Process-based simulation models using BPMN for construction management at runtime

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Abstract
In this paper, we present a platform to develop smart and flexible simulation models, based on the notation known as Business Process Modelling Notation, in support of construction management. They are generated in a way that supports effective re-planning at runtime. They merge information about the product model, construction processes and associated resources. Thanks to the notation used, that information can be properly re-arranged in order to generate the work plan even automatically, e.g. by means of search algorithms. At runtime, the business process models are used to monitor work progress and re-instantiate search algorithms for rapid update of work plans. This notation facilitates construction managers who develop work plans taking into account the usage of resources and of the intrinsic dynamics of construction projects. Finally, the application in the energy retrofit of a residential building is showcased.

Keywords: process modelling, BPMN, construction management, BIM, runtime

1 Introduction

The complex and heterogeneous nature of the construction environment, and the non-linear, complex causal–effect relationships among the project variables and surrounding factors suggest that construction management tools cannot neglect a project's dynamics (Alzraiee et al 2015). The planning function is bound to provide directions to the governing execution processes. Also, workflow controls provide measurement of conformance to directives along with inputs for future and continuous re-planning during execution (Dave et al 2016). In the lean construction approach, workflow variability is caused by an incomplete understanding of how the different elements interact each other. Hence, methods for quick balancing of those flows must be developed (Garcia-Lopez & Fischer 2016). In order to gain in terms of productivity, new practices and techniques, such as BIM, have the potential to break down barriers between previously siloed activities and to provide better integrated and flexible processes (Turner et al 2021). Simulation tools and collaborative platforms to support huge and complex projects with low-cost entry for construction industry is crucial to promote a wider adoption of simulation in construction industry and its supply chain management (Ismail et al 2017).

In this paper, we will showcase the use of Business Process Modelling Notation (BPMN 2.0) as a means for organizing semantically relevant construction knowledge within a BIM environment, and for providing it to simulation models of construction operations. BPMN will establish a link between product digital models and tools for flexible re-planning of work execution at runtime.

2 Literature review

2.1 Modelling complexity in construction works execution

Project plans developed using traditional methods result in models that are discrete in nature and not representative of the system. Traditional methods perform activity-based planning and their failure is attributed to the uncaptured causal-effect relationships among the project variables (Alzraiee et al 2015). Such difficulties are attributed to the complex, dynamic, uncertain and heterogeneous nature of the construction environment (Francis & Miresco 2016). Rather, the dynamics of a construction site can be studied as an emergent property from interactions between resources on site and the environment. Therefore, initial planning is limited to the short term and must be continuously updated with the knowledge of the actual evolving states of the processes and resources. Modeling platforms, such as the 4D approach, appear to be a definite requirement to prevent or resolve uncertainty (Hosny et al 2020). But despite the potentials of simulation techniques, creating reliable, flexible and reusable models is very complex (Lucko et al 2008). In order to help construction managers to account for uncertainty and dynamics, discrete event simulation and system dynamics have been tested. The former is effective in analyzing the stochastic nature of parameters at a tactical level, but it falls short in modelling a project's holistic level as well as the interrelationships among its elements. The latter is a powerful tool for modelling feedback processes in a project, as well as the holistic level of the system (Alzraiee et al 2015). Agent-based modelling is a decentralised approach, where all agents as well as their behaviour and the environment must be identified in such a way that the global behaviour emerges as a result of the interactions of distinct individual units. However, it is currently quite hard to create and it misses a view on global objectives (Ben-Alon & Sacks 2017). In this paper, a stigmergic search algorithm based on the Ant Colony Optimization approach is applied. It assumes that a large number of simple artificial agents are able to build good solutions to hard combinatorial optimization problems via low-level based communications (Gambardella et al 1999), as reported in Section 3.2.3. This approach can find at least a sub-optimal solution within a time slot in the order of ms, and is able to refine such a solution iteratively. This makes the approach suitable for construction management at runtime, as its response can be bound to any time limit that may apply. Capturing data on the progress of construction projects will provide the fuel needed to drive data analytics, so that scheduling algorithms could be deployed to address possible issues arising during onsite construction projects (Turner et al 2021).

2.2 The adoption of BPMN for project planning

The effectiveness of automation tools depends on the availability of simulation models based on a formalized, shared and accepted representation that integrates issues about resources usage, constraints and mutual dependencies among processes and information flows. Also, in a "BIM according to the ISO 19650 series", the CDE solution and workflow must enable the development of a federated information model (BS EN ISO 19650-1). A simulation tool to integrate projects data with low-cost entry for construction industry has been developed under the acronym Construction Simulation Toolkit – CST (Ismail & Scherer 2014). It uses BPMN to capture and arrange the domain knowledge and transform it into simulation processes, coupling logistics and production in one environment (Ismail & Scherer 2017). As compared with traditional techniques (e.g. Gantt charts, PERT diagrams) the process-based simulation allowed by BPMN offers benefits because it can dynamically calculate the duration of clusters of activities, taking into account the real combination of resources. Besides, it supports the application of corrective actions in case of unexpected changes during the construction phase. In other words, the logic underlying the BPMN helps define a flexible schema for resource combinations prior to simulation and scheduling. Finally, this multi-model project planning allows the combination of heterogeneous application models from different domains and various data formats. The graphical representation of BPMN models makes models easy to understand between all involved teams, and the formal specifications in XML allow transforming process models into simulation models automatically.

In this paper, we will report on the development of a management platform integrating extended process simulation models, building models, resource data, search algorithms for sequencing activities. We show that the notation based on BPM to model construction processes facilitates the update of work plans at runtime.

3 Methods

3.1 Data integration across the planning and control phases of the workflow

Assuming the project management processes as suggested by the standard ISO 21500 and shown at the bottom of Figure 1-a, our platform concerns the planning and controlling phases. The former establishes baselines against which project implementation can be managed, measured and controlled; the latter is concerned with monitoring, measuring and controlling project performance in order to define preventive and corrective actions to achieve project objectives. The services provided by our platform vary depending on the project stage, that are articulated as shown in the top bar menu of the platform's UI depicted in Figure 1-b. We assume that we operate in a BIM-ifc compliant environment and that the list of building components to be built or replaced is provided as a starting point, either performed by a specialist planner or through data retrieval queries (Tauscher et al 2016). Firstly, the specialist planner is allowed to cluster such a list into groups of "Deliverables", where every group includes building elements that are built within one of the construction processes described in the next step and around a definite work location. In the next step regarding "processes", the BPMN is used to create semantic and graphic process models for various construction operations. Price list records are associated with every task of these processes to describe the technology and sequence of operations, the crew linked to every task, its productivity and costs. To be noticed that a process can be associated with more than one deliverables, e.g. every group of windows can be replaced using the same set of operations in a construction process, described as one of the BPMs. Thanks to the link among construction processes, groups of deliverables and price lists, all processes are then automatically instantiated into activities and involved resources are organized in the corresponding tabs called "activities" and "resources". Then, data are arranged into a JSON input file to be transferred to an automated planner. This planner implements a stigmergic algorithm (ref. 3.2.3) to find out a work plan including every information about durations, resource usage and job logics. During the control phase, the work progress is recorded and the BPMs monitor the progress in the "Execution" tab. In case of deviations, the search algorithm is re-started to update the work plan.

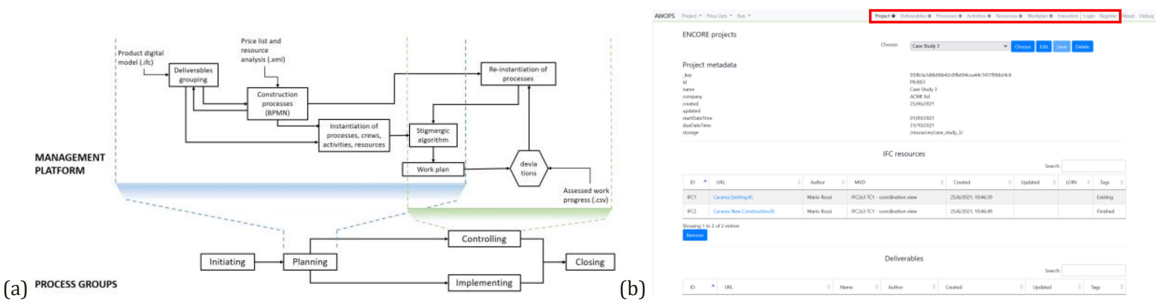

Figure 1. Workflow supported by the platform mapped against project phases (a) and UI of the platform object of this paper (b).

3.2 Architecture of the management platform

The management platform is a web-oriented set of tools (Figure 2) that realizes a layered architecture, made of a bottom storage layer, web-applications at the top, and a set of web-services called the middleware. The storage layer contains information structured either as files, that is common practice in the Common Data Environment approach, where documents and IFC files are stored to form a unique source of truth or as databases, used to store metadata about the project and the involved models. They are ready to be queried and linked together in ways that would not be possible using just files. Our platform uses a NoSQL database as opposed to relational ones. The current implementation relies on the state-of-the-art graph database ArangoDB. The middleware contains web-services that communicate via a REST Application Programming Interface. This is a de-facto standard to ensure a seamless integration among these web-services, the web-applications on the upper layer and external web-services running on different platforms. Two examples of middleware services are the planning service (ref. 3.2.3) and the price list navigation service (ref. 3.2.2). The application layer contains a web-based GUI through which the project manager builds and monitors workplans of the current project.

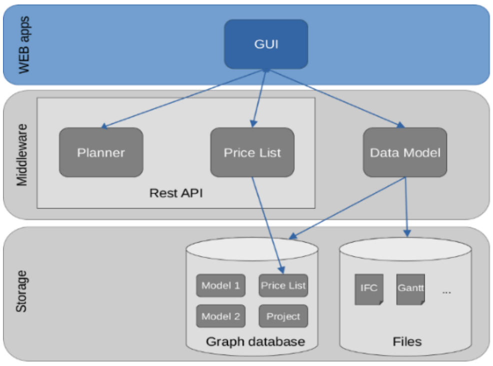

Figure 2. Architecture of the platform developed in this paper, which includes a process modelling unit based on BPMN.

The management platform stemmed from two fundamental design choices: the first one was to formalize a data model for workspace management; the second choice was to provide the project manager with the tools to formally represent, recombine, and link information among the renovation activities exploiting the standard notation for processes BPMN 2.0. The workspace management data model merges and extends the concepts described in state-of-the-art data models (Kassem et al 2015). The BPMN 2.0 construction processes can be executed or simulated exploiting state-of-the-art tools (e.g. the open-source Camunda suite). This standard allows customized extensions to the language, and our platform exploits this feature in order to link processes with activity or resource codes taken from the price lists. Once the renovation work is in progress, the project can be updated with progress information. As shown in Section 3.3, this is used to monitor processes at runtime and, in case of deviations, to generate a new workplan.

3.2.1 Data model for processes, resources and cost analyses

Information about processes, resources, and cost analyses are arranged on a graph structure, thus we talk of the stored and exchanged information as *nodes*. The nodes are stored on a graph database (viz. ArangoDB) and is accessed by means of a RESTful API. Hence, each node is uniquely identifiable over the Internet and can be referred and retrieved from any other (authorized) dataset across the Web. The nodes store the URLs of other nodes they are linked to, thus we are able to simulate a scenario where the information graph is distributed over the Internet, heterogeneous data sources are managed by different organizations, and links between the data cross the organizational borders. The nodes are stored and exposed as JSON documents. Product, processes, price lists with cost analysis and resources are represented and linked as shown in Figure 3. A “Deliverable” corresponds to a set of IFC products and is linked to a process and corresponding activities. Each activity is an instantiation of a process task on a specific deliverable and is executed by a pool of “Operational Resources”. The execution status of the activities is recorded in the “progress” field, valued between 0 and 1, that represents the percentage of completion. The setup time preceding every activity is inferred from the resources model and stored as resource skills. For each activity, the minimum set of required resources and their cost is specified by the price list items associated with tasks. Linkable price lists are represented in XML-based notation, containing a formal representation of the cost analysis tables for each activity in the price list itself (e.g. StandardSix XML Schema). Thus, by linking the business process task to the pricelist item, one can work out the cost analysis of each task of the business processes, and can arrange such information to obtain the cost analysis and resource usage in each construction or renovation process. In the follow-up of this work, we plan to extend the current implementation of the data model by using JSON-LD (JSON-LD, Lanthaler & Gutl 2012), a recent W3C Recommendation allowing to extend existing graphs of JSON documents onto a fully fledged collection of linked data, allowing to query data using standard technologies such as SPARQL or being linked by other RDF triplestores.

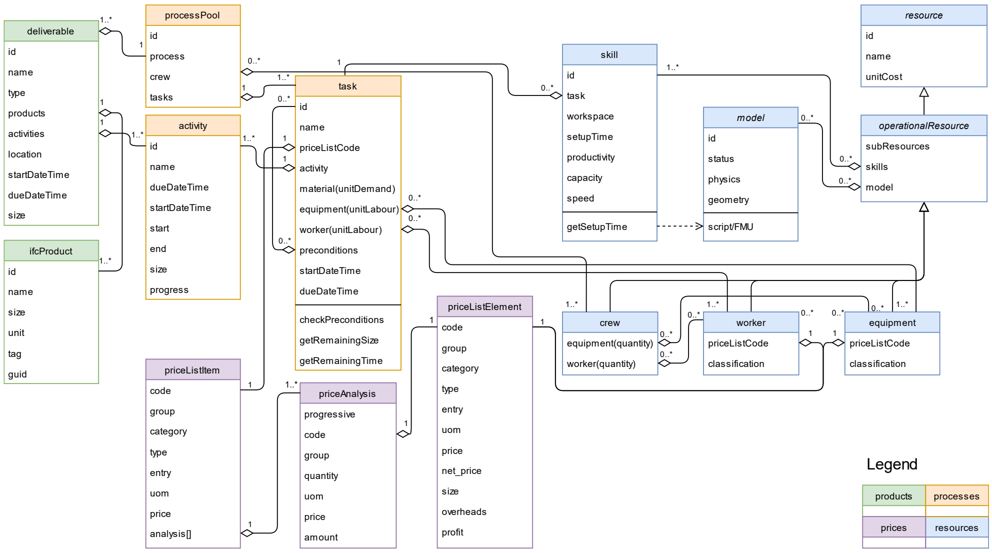

Figure 3. UML class diagram representation of data model for processes, resources, and cost analyses.

3.2.2 Definition of the logic of construction processes

Generating a workplan using a process-based approach ensures better usage of the available resources, as opposed to activity-based (Ismail et al 2017). The core component of the web-application is the BPMN editor embedded in it (Figure 1b and Figure 4). This unit allows the project manager to navigate a catalogue of available construction or renovation processes, customize them for the current project, and even create new ones that will enrich the catalogue itself. A typical BPMN diagram describes the collaboration among several teams. Each team is assigned a pool of business processes, and each member of the team (i.e. actor) is assigned to a lane of such pool. Each lane contains a graph whose nodes represent either a task, an event, or a control structure (i.e. gateway). Such nodes are connected with arrows (i.e. flows) defining what sequence of tasks is being executed. Events are either triggered or observed, while control structures are evaluated. To be noticed that business processes always have a start event, whereas the end event is optional. Other examples of events supported by the BPMN 2.0 standard is sending or receiving messages to and from other actors, setting a timer, reacting to a timer already expired. Thanks to parallel gateways, the process designer can specify two lines of work proceeding in parallel, as opposed to the situation that only one among a set of possible alternatives must be selected. In the BPMN editor, a project manager can specify constraints among tasks of different processes and link each task of a business process to any of the activities described in the reference regional price list. This information is then encoded as a JSON object and sent to the planning web-service reported in Sec. 3.2.3.

3.2.3 The simulation model for planning at runtime

The several knowledge bases managed by the platform provide information that is used to invoke a planning web-service that returns a feasible strategy for executing the construction or renovation activities with a defined resource pool, as reported in sections 3.2, 3.2.1 and 3.2.2. The planning web-service makes use of a metaheuristic approach inspired by the foraging behavior of real colonies of ants (Naticchia et al 2019). This algorithm handles the complexity of the planning problem by using stigmergy: a mechanism of indirect coordination used by insects and mediated via the environment. An ant colony consists of several ants that looks for a solution of a given problem. When an ant explores the whole environment and finds a solution, it leaves pheromone trace on the path whose strength depends on the goodness of the found solution; this trace affects the performance of the subsequent search by the same or other ants. As a result, the colony quickly finds a feasible solution that can be continuously updated and improved as new information arrives. Each solution is based on the previous one and tries to stick on it whenever possible and when no significant improvement is achieved. The planning algorithm is based on the multiple ant colony system for vehicle routing problems with time windows (MACS-VRPTW), as proposed in (Gambardella et al 1999). In our implementation, each *customer* corresponds to an *activity* of the work plan to be executed in the given *time-window*; there is only one virtual *vehicle* that must serve all the customers and *travel time* is replaced by the total *cost* of the work plan. Since only one virtual vehicle is present, the ACS-Time colony was implemented. Each activity connects a *deliverable* to the involved *crew*. The local search option of MACS-VRPTW was not implemented since the actual execution is established by the workers based on many unpredictable events and could differ from the plan more than the entity of these adjustments. Some enhancements, proposed in previous works (Naticchia et al 2019) have been here adopted. Denoting with a_k^i the i-*th* activity of ant a_k, the cost is computed as:

$$cost(a_k) = \sum_{i=1}^{n} \left(endTime\left(a_k^i\right) - departureTime\left(a_k^i\right)\right) \cdot hourlyCost\left(crew\left(a_k^i\right)\right) + \max_{i=1..n} \left(endTime\left(a_k^i\right)\right) \cdot hourlyCost(site) \quad (1)$$

The first term of Equation (1) represents *direct costs* and include those costs that are generated by displacements between workplaces, waiting times (e.g. whenever constrained by previous tasks) and operation. The second term represents *indirect costs* which depend on the elapsed working time. Constraints due to *prerequisite activities* established by the construction process have been added to enforce the correct operation sequence. The best solution is re-evaluated, compared, and updated at each call of the service and at each iteration to perform dynamic planning in case of unexpected events or as soon as work progress data are available.

3.3 The case study

The case study is relative to the energy refurbishment of a residential building located in Caceres (Spain), which is also the pilot of the EU funded project Encore (Encore project). In this specific case, the tool Autodesk Revit™ was used by the research team to develop the virtual building model of the existing conditions (i.e. Existing phase) and then to model the refurbishment actions (i.e. New Construction phase), as displayed in Figure 4. The retrofit actions consist in the replacement of three existing layers (i.e. drywall, air layer, thermal insulation) of the envelopes with thicker ones, including the air layer of the north and south façades. Irrespective of the authoring tool used to develop the model, the input files required by the platform is made of an ifc file of the existing building and another ifc file of the renovated building. A couple of files must be exported by the authoring tool for each discipline, e.g. architectural, MEP. In the specific case of this paper, while exporting the ifc file of the "New Construction" phase, some technicalities had to be taken into account. First of all, the existing walls were split into discrete parts that can be independently edited and the options that exclude the demolished layer during the exportation process were ticked. Secondly, the "demolition phase" was assigned to all the existing windows and shutters to be replaced. The new window family has been loaded onto the project and new types have been created. A family for automatic solar protections and shadings has been modeled and four new types have been created, suitable for the windows on which they must be installed.

The third action concerns the installation of a solar chimney. A 10.4 m high solar chimney type has been created and placed on the south façade. The fourth action concerns the installation of an air supply system. The architectural ifc file relating to the "New Construction" phase has been linked to a new mechanical model. For the purpose of the proof of concept showcased in this paper, only the first two retrofit actions, out of the four described above, were considered, i.e. the retrofit of the facades and the replacement of windows.

3.4 Setup of the experiments and implementation

3.4.1 Generation of the first work plan

As mentioned in section 3.1, the first tab of the platform called "Deliverables" (Figure 1b) includes the list of building components to be built or demolished. The user, that is presumably the project manager or project engineer, is in charge of clustering the aforementioned components into deliverables. The basic specification for a cluster is that a crew will work the selected components within the same BPM and keeping the layout unvaried. In other words, building elements that share both the same work category and work location are clustered into one deliverable. Then, each one of the two retrofit actions addressed in this paper was described as a BPM that models the sequence of construction operations that produce each type of deliverable (i.e. envelope renovation and window replacement). As shown in Figure 4, the notation of BPM is made of start message events, tasks (e.g. concerning the removal of existing wall layers, installation of the metallic bearing sub-system, the waterproofing membrane), parallel gateways to indicate that some tasks can be performed concurrently; end message events. Constraints are defined by combining a parallel gateway icon and an intermediate message event, such as in the case of the installation of the metallic bearing sub-system, that cannot start until the respective elements have been delivered on site.

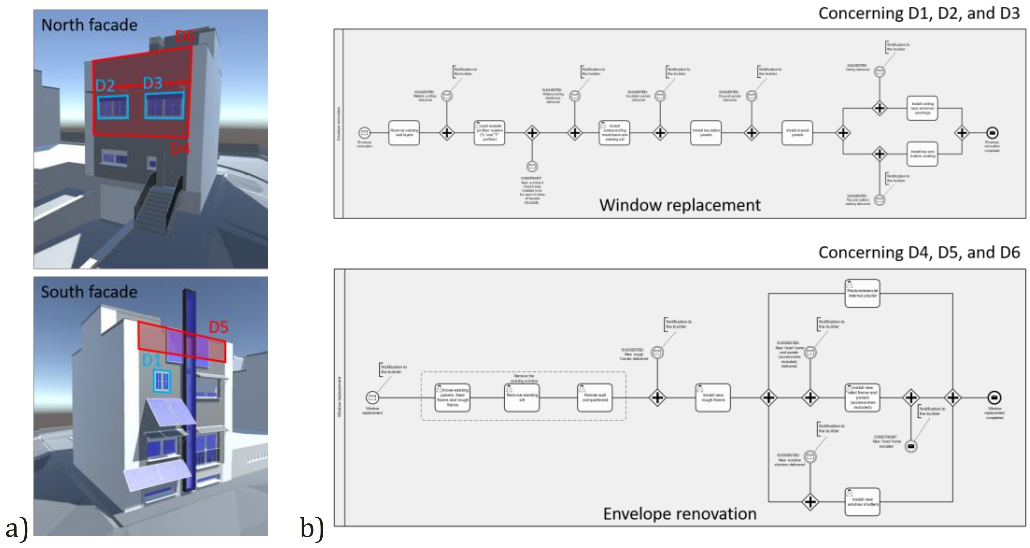

Figure 4. Graphic representation of the deliverables for the case study (a) and BPM relative to the actions "envelope renovation" and "window replacement" (b).

These tasks have been linked to the corresponding items of the price list. As the price list of the area in Caceres (Spain) is not available in an open and structured format (Caceres 2021), the subset of items relevant for the case study and the cost analysis relative to every item were rearranged according to the XML schema of the price list of Tuscany region (Regione Toscana 2021). Thanks to this rearrangement, the items of interest were linked to tasks and, then, to resource requirements and analysis. As price list items are linked to the cost analyses of crews in their own repository, the platform automatically evaluates the minimum composition of crews. Every BPM corresponding to any type of deliverable shall be replicated in the form of as many instances as the number of occurrences found in the list of deliverables. As for the case study (ref. 3.3), three instances for each deliverable of the types "envelope renovation" and "window replacement" have been created. Transfer and setup times, required by any crews to move between work locations, have been estimated based on a predefined movement speed and on the distance between work locations. As a result, all the information described above was provided as an input to the planner, which implements the ACO algorithm reported in Section 3.2.3, and arranged within a JSON file. The output of the ACO algorithm is depicted in Figure 5 as a work plan represented by Gantt Charts and Flow Lines (see Figure 5).

3.4.2 Assessment of the system in the execution phase

Some benefits of this system have been assessed at the execution phase. Hence, the updating procedure of the workplan at runtime was simulated. As displayed in the baseline depicted in Figure 5, an intermediate "as-built" scenario is defined at hour 9, that is at the end of the window replacement on D 1 (see red dashed line in Figure 5). The actual progress is represented as solid green bars. The delay of D 1 would cause additional delays on the start of deliverables D 2 and D 3, assigned to the same crew no. 1. The straight shifting of connected activities would cause D 2, D 3 and D 4 (this one performed by crew no. 2) to be shifted ahead.

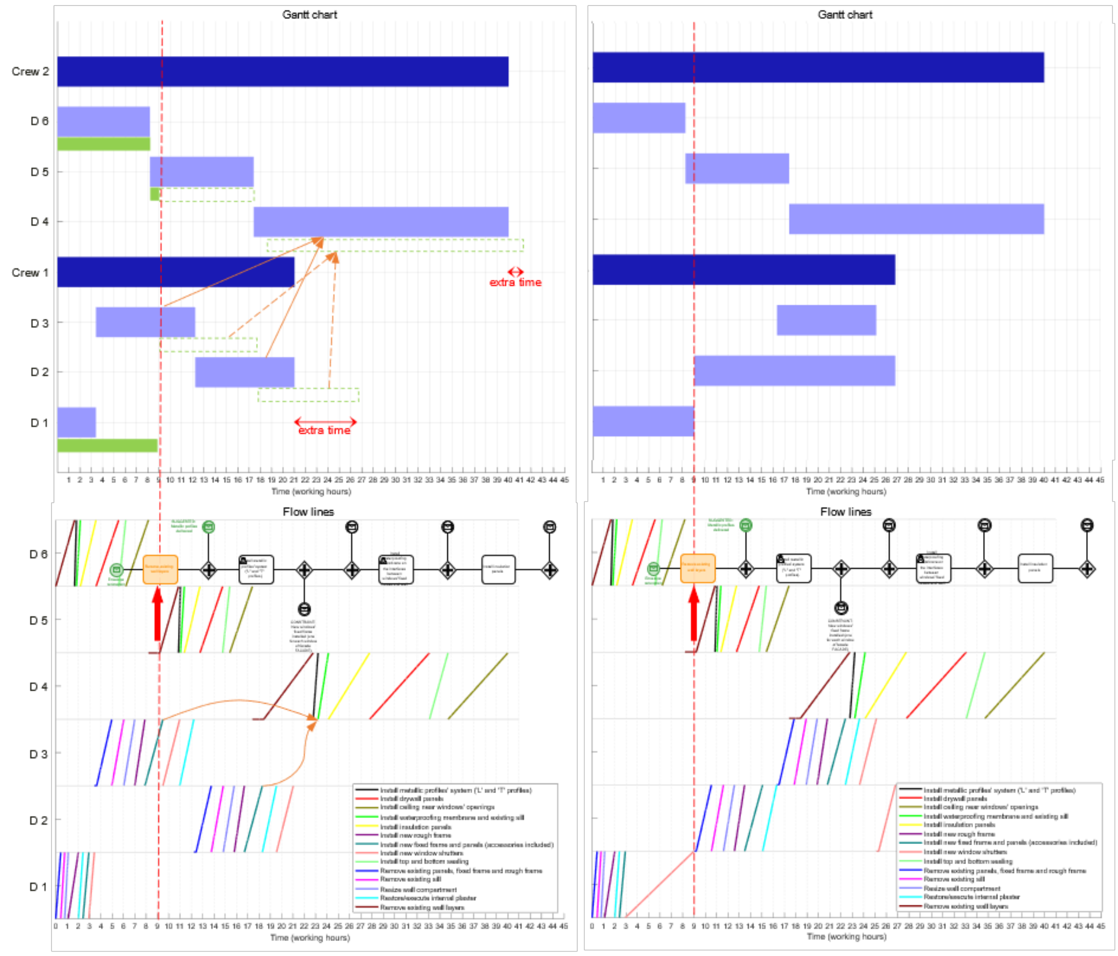

Figure 5. Baseline relative to the energy retrofit actions represented as Gantt Chart (top) and Flow Lines (bottom). The dashed red line identifies the progress at hour 9, which determines shifts of activities as shown by green bars. Orange arrows show two critical links among activities that would cause the shift of deliverable D4. It can be noticed that the expected overtime was addressed by re-planning activities assigned to crew no. 1, without affecting activities in charge of crew no. 2.

On the contrary, the platform monitors the work progress using the BPM at the "execution" phase. It recalls the planning tool at runtime, based on the intermediate "as-built" scenario, and works out the new workplan for the remaining work reported like in Figure 5 (bottom line). In the new workplan, the assignment of crew no. 1 is changed, as a consequence the activities assigned to the envelope renovation's crew (i.e. crew no. 2) are not delayed any longer. In other words, the planner changes the task logic and suggests interrupting the window replacement activity of D 2 and moving to D 3, so as to meet the technological constraints required by D 4 and avoid idle time for the assigned crews. The BPMs superimposed over the Flow Lines in Figure 5 represent progress monitoring by using different colors according to the work progress: green nodes represent completed activities, orange ones are those in progress, whereas white ones have not been started yet.

4 Findings

The platform described in this paper supports the planning and controlling processes. It integrates a stigmergic algorithm to enable automatic re-planning of activities to generate a baseline, and then, during works progress, to respond to deviations. The main advantages of this platform consist in:

1. Collecting information about deliverables and resources within a unique framework.
2. Supporting resource planning by means of flexible simulation models.
3. Facilitating monitoring through BPMN, which is a prerequisite for re-planning at runtime.
4. Arranging information properly thanks to BPMNs that can integrate data about work progress and trigger the planning algorithms to update the work plan.
5. Storing process models as a "ready to use" catalogue, also across different projects.
6. Dynamically calculating the duration of every activity during the simulation, taking into account the real combination of resources to be involved in the execution phase.

The only drawback is that linked resources are often not structured into schemas (e.g. the price list used in Caceres, Spain) and this hampers the applicability of the platform. Also, in order to reach the full automation of the approach, some technology for fine-grained work progress monitoring must be developed.

5. Conclusions

Thanks to this platform, work plans can be worked out with the support of search algorithms that are able to perform "what-if" analyses and decision making. In case data are collected according to a predefined schedule and arranged at runtime, the BPMN can constitute the core of a framework that quickly triggers look-ahead simulations and assesses whether there is room for improvement in the planning of remaining tasks. In addition, the formalism known as BPMN is able to elicit the subjective knowledge of the project manager or project engineer, as long as he/she makes a decision concerning the activities to be performed during works execution and their link to deliverables. The main limitation of the approach reported in this paper is that a collaborative environment supporting the project manager in the tasks of checking and approving work plans is still missing. The second limitation is that our application of the BPM notation has been focused on the execution phase, whereas the other phases of project management were not considered. Among the foreseen future developments in the short-term we cite the development of a collaborative environment. Other advances concern the integration of this tool in the next generation of policies for management practice through the application of digital twins (Turner et al 2021).

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