Rossini, F. L. & Novembri, G. (2023). Construction productivity graph: a structured framework to enhance productivity and safety on construction sites. *Proceedings of the 31st Annual Conference of the International Group for Lean Construction (IGLC31),* 186–196. doi.org/10.24928/2023/0232

CONSTRUCTION PRODUCTIVITY GRAPH: A STRUCTURED FRAMEWORK TO ENHANCE PRODUCTIVITY AND SAFETY ON CONSTRUCTION SITES

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ABSTRACT

The construction industry is characterised by the constant production of unique products in dynamic contexts where, moreover, the workplace coincides with the product itself. This limits the adoption of standardization and process automation methodologies. Furthermore, the average size of professional firms and companies often does not allow for investments in process innovation or skills development. Then, we need to consider that construction is a highly risky activity, also to the lack of standardization as aforementioned.

The paper aims to present the framework of a methodology based on linking the information managed by a BIM model with Agent-based simulation techniques - ABS. The scope is to simulate the duration of the work under efficient conditions, understood as the best occupation of the available areas by a suitable number of workers. The result is the Construction Productivity Graph - CPG, a graph that indicates the optimization level of the construction process.

KEYWORDS

Project construction management, agent-based modelling and Simulation, health & safety management, location based management – LBM, business process modeling – BPM.

INTRODUCTION

Nowadays, the situation of the construction industry sees an important recovery in demand against a significant increase in the cost of raw materials. This, combined with the difficulty in finding skilled labor, has led to a significant increase in costs, after decades of stagnation and recession in the construction sector.

This situation leads to a renewed interest in reducing the resources to be used in building processes, above all by aiming to reduce waste in terms of materials and time spent.

This research has the objective of saving resources by optimizing construction times, intervening through more efficient management of the work areas. At the same time, it is important to reduce interference, an important cause of injuries during construction works. So, the optimized management of the areas also brings a higher level of safety, given by the lack of overlapping of activities with different risks which, if overlapped, can cause accidents. Finally, especially in the early experimental stages, it was possible to verify how this type of approach also leads to an optimization of the supply chain, due to the possibility of managing the material storage areas in a better way and reducing wasted time due to inefficient material handling.

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(Amiri et al., 2017) and the reworking activities due to variations, which can also result from design errors (Scherer & Schapke, 2011). This issue is known in the building industry for decades, finding a whole series of answers in the application of lean methodologies. However, their diffusion is affected by the traditionally low interest of the construction industry towards technological innovation. Furthermore, it should be considered that these approaches still require investments which, in an economic context that sees companies fragmented in size that limit the possibility of investments, ends up always believing in consolidated procedures or, in the worst-case scenario, evaluating the inefficiency more cost-effective. Finally, it should be noted that a process supplied with optimization methodologies has a lower accident rate, due to the organizational level that lie beneath optimization techniques in general (Elghaish et al., 2019).

An important contribution to process optimization has been given by the growing diffusion of the BIM methodology. This allows the exchange of information through a single and shared model, on which a whole series of verification and analysis activities capable of increasing productivity and the reliability of results can be activated.

In the proposed framework, the BIM model is connected to an agent-based simulation model via API. Each component of the model is connected to an agent equipped with rules, objectives, and behaviors to achieve them. These aspects, typical of agents, allow the model to adapt to any changes in objective (design intent) and context (BIM environment). Furthermore, the agent can carry out self-test activities, and therefore dynamically verify the maintenance of any parameters set by the designer.

Once the characteristics of the project have been defined, the agent model activates a 'Master Actor' who, being hierarchically above the others, has the role of activating the agents who represent the working groups. These are related to the work to be carried out in the assigned work area (location) therefore the agent system defines the duration and the number of resources foreseen. The result is the representation of the Construction Productivity Graph - CPG, a synthesis of these computational processes aimed at explaining the location of tasks and the appointment of the number of workers per construction site area. The dynamism of this methodology is therefore useful not only in the design phase, but also during the execution and management of the construction site, since it is sensitive to variations, unforeseen events and changes of objective, through continuous and traceable updating of the project database (BIM model).

BACKGROUND

About Advancement of Lean Construction

The lean methodology is based globally on the reduction of waste that can be generated along the course of a process. The objective is in optimizing of the chain of labor and the reduction of resources employed to parity of result, more and more current thing in consideration of the current scarcity of energy and raw materials (Carvajal-Arango et al., 2019).

From the point of view of building production, optimizing processes also means taking care of the quality of concrete production operations, with repercussions on safety and quality of working life in general. So (Schimanski et al., 2021) analyses that, in the construction industry, the most widely used lean techniques are Just In Time - JIT, Total Quality Management - TQM and Location Planning System - LPS. In addition, from the experience of the years of the pandemic there is a growing interest in Agile, thanks to the rapid introduction of the techniques of dematerialization of processes even in a very traditional and focused on the real site, such as construction sector is. The growing, spreading of BIM then led to the development of specific prototypes such as KanBIM (Gurevich & Sacks, 2014). The goal of KanBIM is to control the workflow and visualize processes parameters inside a BIM model, where their entities represent the information database of the whole system. However, by analyzing the comparative tests produced on these tools, we can see that the main issue is the link between the BIM entity and the production of the optimized process diagrams according to Lean logic (Babalola et al., 2019).

The advantages of these methodologies, considering the current level of development and definition, concern above all a better control of aspects such as space management, the effectiveness of the logistic chain and an improved responsibility of the technical figures involved in the working phases. From the point of view of the management of workforce, we can see - from the cognitive point of view - a possible drop in attention and operational responsibility on the part of workers, due to the repetitive and constant application of work patterns set by the system. This, combined with a lack of training, can lead to less reactivity and efficiency in case of exposure to unforeseen risky situations (Celik & Gul, 2021).

One of the most common causes of accidents on site is linked to the failure to manage interference, both from a spatial and temporal point of view. The construction site, unlike the industrial production line, is extremely dynamic and susceptible to having work crews interfering in the same area, but with different risks. Furthermore, consider how much the human factor can still influence the risk conditions in the building industry, another factor to be limited with the increase in automation in the building industry, a further reason for encouraging the introduction of industry 4.0 protocols to encourage continuous and constant connection between the forecast/simulation model and the reality of the construction site, with a view to the preventive reduction of overlapping situations. (Pregnolato et al., 2022). A desirable goal is therefore to find a meeting point between human awareness in the management of repetitive actions, and process optimization understood as the systematic adoption of techniques and methods that are easily repeatable by workers, and which can also be transferred to worksite machines that can gradually be inserted into the work site, even as physical support for workers (eg. Exoskeleton) or wearable technologies in general. (Aguirre-Jofré et al., 2021).

The limits of this approach are the cost of installation and management, which are too expensive for small works, and to be applied in socio-economic contexts not technologically developed. Another important limit is the broadband availability, essential to ensure this flow of information. In construction works located in historic contexts, where thick walls or underground areas are present, it is difficult to ensure a complete ICT accessibility. It will be necessary to start thinking about site data networks intended as networks to be installed in parallel to the electrical ones, for making each point reachable by digital devices, also for linking these detailed models as required by the Digital Twin approach.

AGENT-BASED MODEL INTEGRATION FOR OVERCOMING THE LIMITS OF THE STATE OF THE ART

A possible limitation of the above simulation models lies in the low weight assigned to the management of the working areas and tasks carried out by the workers, and in general for the management of overlaps. These, in addition to slowing down the working process and therefore the general quality of it, cause inefficiencies for the management of the supply chain, due to a reduced optimization of the spaces and therefore of the temporary storage space of the site.

The goal of an agent system is to predict the emerging behavior of the model (Khodabandelu & Park, 2021). This model is composed of agents, rules, behavior understood as the actions that enable the agent to comply with the rules and goals (Grignard et al., 2022). Of course, agent modelling is not the only way to introduce productivity into the decision-making process, as there are a whole series of methodologies that serve the same purpose, moreover they have already tried and tested in the manufacturing sector and considered for the construction sector such as Discrete Event Simulation - DES and System Dynamics – SD (Lyneis & Ford, 2007). DES and SD follow a top-down approach, in which a system is built at the macro level at the beginning, then hypotheses are proposed, and its validity is measured, which is deeply based on empirical analysis, thus being affected by the implicit knowledge of the technician setting the model parameters (Fortino et al., 2005). Agent modelling follows the bottom-up approach, where the basis is the agents and the choices made to achieve their objectives in a heterogeneous or homogeneous/consequential manner, as is the case when pursuing swarm behavior (Zhang et al., 2019).

One of the fields in which the ABM approach is related to the solution of problems in the multi-options field, due to its ability to adapt the behaviors of the agents according to the different rules and objectives, according to the scenario. This dynamism makes the ABM simulation approach closer to the current building design and production, which is always determined by a constantly evolving context. In fact, while other simulation techniques tend to represent standardized actions in homogeneous contexts, the ABMS allows the modeling of the rules individually, and verifies the behavior of the agent both as a reaction of the individual to external stress, and through the verification of adaptation of the whole system with respect to external stimuli (Mathieu et al., 2018). However, ABM, following a bottom-up approach, can establish the interactive properties and characteristics of agents from the level of simple, reciprocal interactions, and thus produce an emergent result at the macro level. This characteristic makes ABM a preferable solution for the activation of what-if computational processes, without relying heavily on empirical analysis, excessive assumptions or directing the model in a preordained and biased direction (Khodabandelu & Park, 2021).

In conclusion, thanks to the ABM, the management of interferences for safety purposes can be much more accurate since it is effectively linked to dynamic changes in the context, and useful for the continuity checks that must be carried out to verify that the site is compliant with the H&S rules. At the same time, it is possible to increase the reliability of the forecast of the spaces occupied for the storage of materials and the installation of components, with related advantages over the management of the supply chain.

METHODOLOGY

The aim of the research is to set up a methodology potentially able to reduce the uncertainties in building production, above all when given by the lack of knowledge of the positioning of the personnel and of the equipment used. The result is a constant check, conducted by the agent system on the data flow provided by the BIM model, with respect to compliance with the needs of productivity and compliance with safety. Then, it is possible to further improve the synergies between the detailed progress of the works and the evaluation of the interferences of risk prevention. From this point of view, the first phase of the work consists of an accurate modeling of the site and the building, for having a reliable match between the reality and the digital model. (Abune'meh et al., 2016). Therefore, the first phase analyzed concerns the expected modeling specifications, where the level of detail of the BIM elements must follow the overall needs, assuming for the identified purpose an always very high level, bordering on the needs related to facility management. These elements are then managed by a Work Breakdown Structure - WBS, capable of linking the properties of the element with the workings connected to it. Following consolidated workflows, the federated model (i.e. The model includes the various WBSs for the different technical domains), is subjected to clash detections, aimed to filter critical issues in the project right from the start. The positive contribution that the implicit (i.e. Subjective) knowledge of the human designer can give, which includes his evaluations, is not overlooked. These are useful both for the purposes of improving the project being defined, and for training a possible machine learning engine towards more suitable solutions in similar future cases. (Figure 1). Once a BIM model suitable for construction analysis has been got, agent-based simulations can be activated, which will define the number of workers required to perform the planned activities in the respective locations (Antwi-Afari et al., 2018). The location is the functional unit of the construction site, a set of locations encompassing homogeneous work where resources can be allocated. Once the work to be carried out in the locations has been organized, the system automatically starts the verification of the propaedeutic and proximity to the horizontal and vertical communication ways of the construction site, for reducing wasted time and interference that may arise from the mere transit of materials through the site.

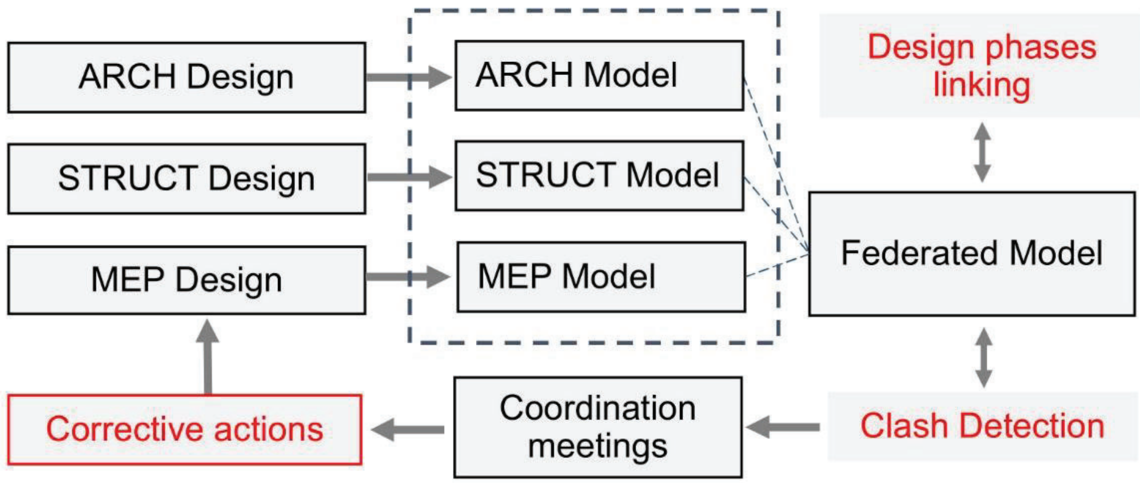

Figure 1: summary of the BIM model checking process.

BIM MODEL VALDATION THROUG MICROSERVICES

This paper describes the methodological approach for a future case study to be applied to a real construction site. The first step consists in importing a BIM model with a minimum LOD of 400, for having a sufficient level of information due to a consistent checking phase, and at the same time enough information to feed the proposed simulation system, or other linked machine learning based tools.

To manage this huge amount of information, often coming from different actors and, above all, subject to numerous updates and alignments during the phases from design to construction, the two approaches of the BPMS protocol can be taken into consideration. The first concerns a centralized orchestrator, where there are a whole series of microservices that gravitate around a centralized management system. The second instead appears as a choreography of microservices where, in a circular and one-way direction, there is a continuous exchange of information where the previous actor updates/modifies the information and sometimes the actions of the predecessor.

The result of the comparison showed that, in this specific case, it was preferable to set up a centralized microservice orchestrator for a matter of scalability of the system and identification of the contribution of the single microservice (Figure 2).

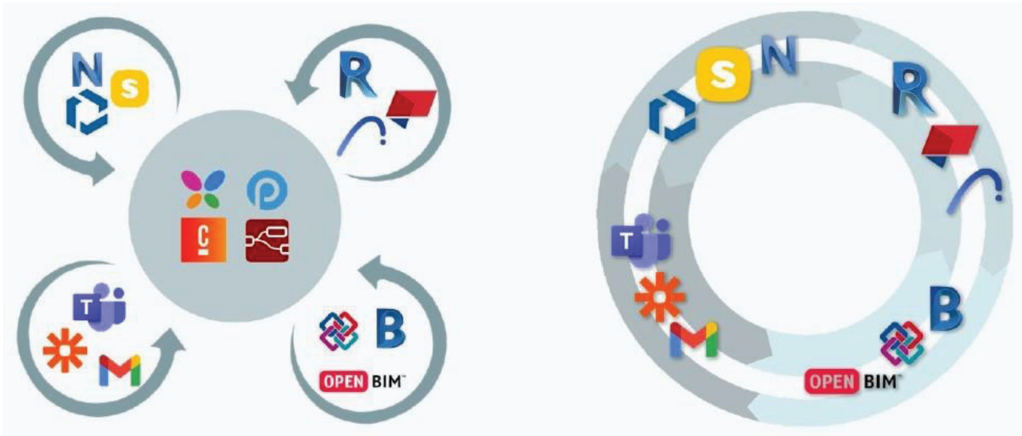

Figure 2: On the Left, the Conceptual Schema of a Centralized Orchestrator; on the Right the Choreography One.

AGENT MODELING FOR THE ASSIGNMENT OF LOCATION AND CREWS

Orchestration using microservices allows you to conduct a whole series of updates, variations, and checks without risking major project inconsistencies. Of particular importance will be the verification of correspondence between BIM elements, possibly updated with respect to all the checks carried out, and the connected work activities, according to the WBS approach.

The analysis of the workings is of particular importance for the subsequent modelling phase of the agents, since they will have to adapt their behavior with respect to the specific rules of the workings, both in terms of productivity and in terms of safety.

Once the modeling of the rules and behavior of the agents has been completed, their activation will be delegated to a Master Actor who, according to the logic of the actors, manages the workflows by activating or not the agents, according to the breakdown into phases envisaged by the WBS. Therefore, we model the WBS themselves as Agencies, i.e. Systems that contain within them other agents that represent simple components and elements. The most important rules regarding the location of the intervention, the productivity of each working team and the need for operating space, and the respect of priorities or the sequence in general of the work activity analysis. The establishment of these rules is decisive for managing the optimization of times and resources, given that a large part of the optimization conditions derives from the possibility of using multiple locations, managing interferences and the possibility of using shared logistic conditions to reduce the areas transit and handling of loads on site, conditions characterized by a high risk of accidents. This activity also helps to correctly evaluate the lost time of transport within the site. The result is the production of a table that summarizes the number of resources to be employed, the location to occupy and the duration of the work. (Figure 3).

Starting Date		1	2		2	3		3	4	
17/11/2022 8.00	Location 1 (2h)	Location 1 Start	Location 1 Finish	Location 2 (2h)	Location 2 Start	Location 2 Finish	Location 3 (2h)	Location 3 Start	Location 3 Finish	Location 4 (2h)
Task 1	32	17/11/22 8.00	21/11/22 13.20	32	21/11/22 13.20	24/11/22 10.40	32	24/11/22 10.40	29/11/22 8.00	32
Task 2	38	16/12/22 10.40	19/12/22 15.20	38	19/12/22 15.20	21/12/22 12.00	38	21/12/22 12.00	23/12/22 8.40	38
Task 3	105	3/1/23 16.00	6/1/23 13.00	105	6/1/23 13.00	11/1/23 10.00	105	11/1/23 10.00	13/1/23 15.00	105
Task 4	25	16/1/23 8.00	18/1/23 8.40	25	18/1/23 8.40	20/1/23 9.20	25	20/1/23 9.20	24/1/23 10.00	25
Task 5	50	7/2/23 13.20	10/2/23 14.20	50	10/2/23 14.20	15/2/23 15.20	50	15/2/23 15.20	21/2/23 8.20	50
Task 6	72	23/2/23 8.00	27/2/23 8.00	72	27/2/23 8.00	1/3/23 8.00	72	1/3/23 8.00	3/3/23 8.00	72
Teams Name	Members									
Team 1	3	17/11/22 8.00	21/11/22 13.20	24/11/22 10.40	29/11/22 8.00	1/12/22 13.20	6/12/22 10.40	9/12/22 8.00	13/12/22 13.20	16/12/22 10.40
Team 2	6	16/12/22 10.40	19/12/22 15.20	21/12/22 12.00	23/12/22 8.40	26/12/22 13.20	28/12/22 10.00	29/12/22 14.40	2/1/23 11.20	3/1/23 16.00
Team 3	10	3/1/23 16.00	6/1/23 13.00	11/1/23 10.00	13/1/23 15.00	18/1/23 12.00	23/1/23 9.00	25/1/23 14.00	30/1/23 11.00	2/2/23 8.00
Team 4	3	16/1/23 8.00	18/1/23 8.40	20/1/23 9.20	24/1/23 10.00	26/1/23 10.40	30/1/23 11.20	1/2/23 12.00	3/2/23 12.40	7/2/23 13.20
Team 5	4	7/2/23 13.20	10/2/23 14.20	15/2/23 15.20	21/2/23 8.20	24/2/23 9.20	1/3/23 10.20	6/3/23 11.20	9/3/23 12.20	14/3/23 13.20
Team 6	9	23/2/23 8.00	27/2/23 8.00	1/3/23 8.00	3/3/23 8.00	7/3/23 8.00	9/3/23 8.00	13/3/23 8.00	15/3/23 8.00	17/3/23 8.00

Figure 3: The Output of the Agent-based Simulation, Indicating Tasks, Locations and Time Needed.

Once the number of workers has been got from the agent system in relation to the work to be carried out for each location, a new micro-service is activated, aimed at the graphic visualization and verification of interference in relation to the activities expected for each location and the number of workers used. Simple spreadsheets on accessible and widespread formats such as *.xlsx were used to define these graphs. From there, the Location Based Structure is set up, so that the duration of work, the maintenance of the optimal workflow average and any overlaps can be fully visualized.

After an initial series of inferences, the agent system establishes a balance between the number of workers, the duration of the activities and the occupation of the areas. Once this information has been defined, graphically represented according to the standards of the Location Based Structure, in order to verify, also graphically, the existence of overlaps or interferences, as well as the possibility of having the expected number of workers.

To define these graphs and make them as interoperable and accessible to as wide an audience as possible, simple spreadsheets in *.xlsx format were used.

The first result shows the expected number of people, the duration of the work and the teams involved (Figure 4), according to simple straight and oblique lines. This type of scheme is unique for each location, and in any case already guarantees, at a local level, initial checks on compliance with the maximum number of people allowed on site, on the equipment and on the possibility of managing areas for the storage of materials. Once the congruence of the works inserted in the individual areas has been verified, we can enter the result relating to the entire construction site into the system, to have a complete view of the optimized consecutiveness of the works.

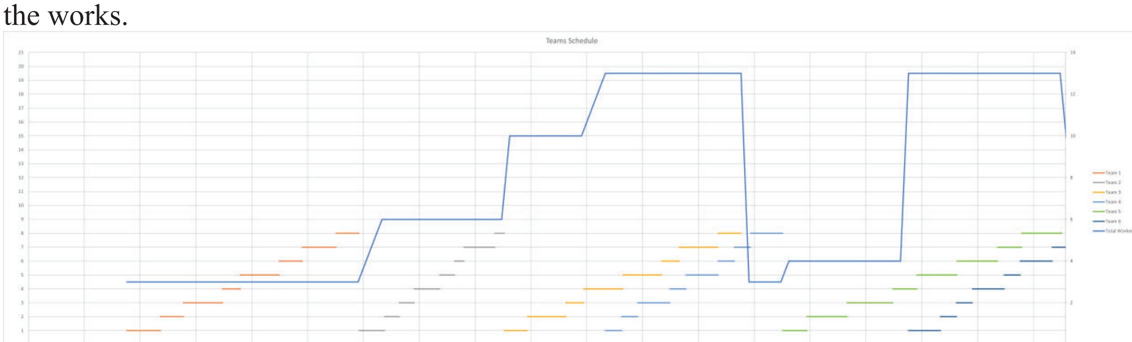

Figure 4: CPG Sample: in Blue the Number of Workers; the Horizontal Lines Describe the Duration of Tasks and the Team Involved. Analysis Conducted for a Single Location.

A further step is the one-to-one link between these results and the BIM model, especially if it is not possible to proceed with the forecasts resulting from the simulation phases.

The objective, through the APIs of the BIM editors used, is to update the simulations on the basis of the information contained in the objects and also the opposite, so as to make the simulation model not only a tool for verifying and organizing the phases of processing, but also a design support, in the sense in which the BIM object can be adapted to the production and safety needs of the construction site..

DISCUSSION

In a first development of this framework, we can observe an underestimation of the productivity reduction factor due to peak occupancy, and an overcrowding in certain areas that are also at high risk, such as in the hypothesis as shown in (fig. 05). Further improvements of this study will keep in analysis, real construction sites and their development compared to forecasting.

We can overcome this type of weakness could through the improvement of the predictive model techniques based on Bayesian statistics. So, in this way will be possible to enhance the correctness of a forecast produced by Bayesian analysis of previous similar cases. These forecasts will be based on expert judgement and the combination with the context. Finally, the future works need to overcome those issues:

- Scalability of the system: considering the large amount of detail required for BIM and agent modelling, there are major limitations regarding the machine's ability to process such large data volumes in a relatively short time. It could be interesting to evaluate the development of digital meta-models, in which will be show representative values of the project, to carry out rapid assessment, creating a new design level named ‘constructive feasibility’.
- Forecast accuracy: to have an adequately accurate forecast model, it is necessary to feed the database of similar events with a good amount of data, as is for the ‘big data’ approach. This consideration may find many practical obstacles, since the construction plans of construction sites, execution methods and metrics of executed projects are sensitive information, proportional to the intended use of the building itself, and therefore problematic to publish. Likewise, it is difficult to create a common data sharing environment from the point of view of the production process of construction companies, which have part of their capitalization and value in the construction and maintenance of best practices and standardized procedures. So, it would be interesting to consider a free digital platform of references in this sense, produced by public institutions that, depending on the type of intervention carried out and the sensitivity of the building, could make available on an open platform with all information necessary to train data libraries dedicated to the construction elements of the building, and to the related agents and rules.
- Auto-generative knowledge: it would also be interesting to gather the experiences gained on the building site itself, and to consider these as a basis to improve the decision-making process for the following construction phases.

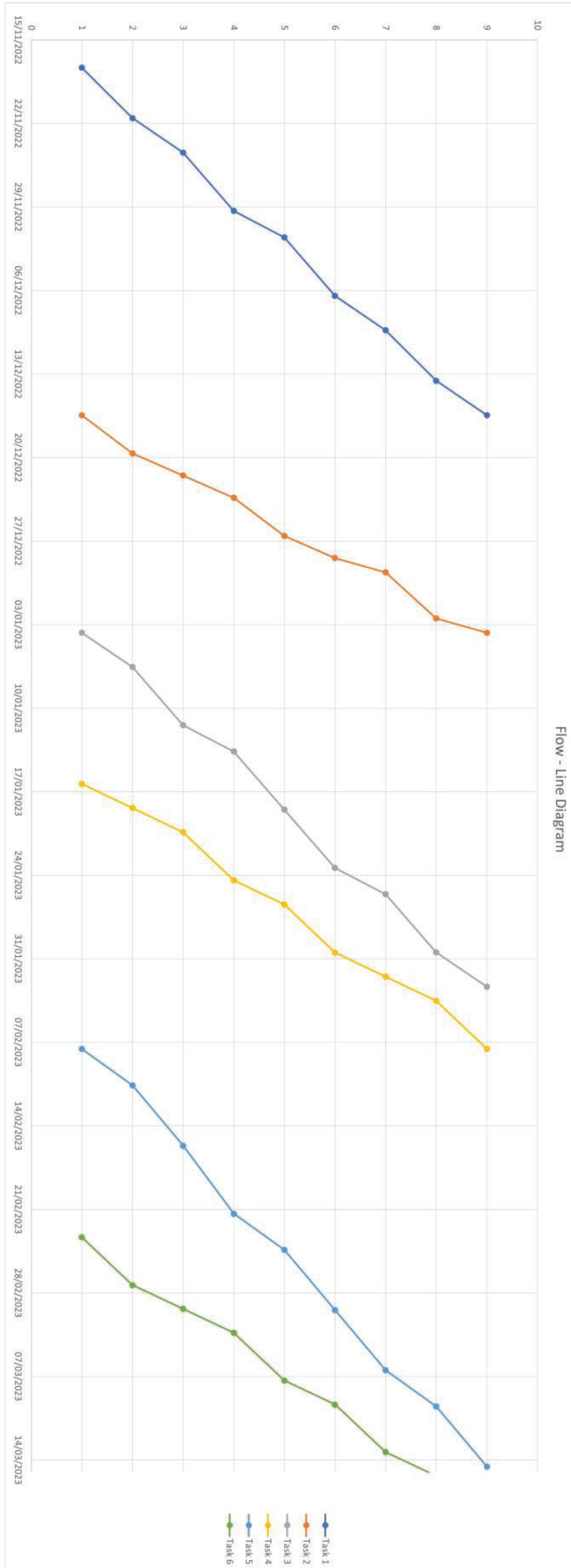

Figure 5: An Overview of the Line of Balance of the Site.

CONCLUSIONS

The proposed methodology takes as its reference the best practices related to lean construction applications, from which derives the conceptualization of CPG. In this management process, the BIM model is the accurate database from which to take and input data following the processing of the ABM simulation results. This information flow, guaranteed by the service orchestrator and managed via APIs, opens interesting perspectives from the point of view of the method's subsequent evolutions. Thus, other micro-services could be added to the workflow, to make the results increasingly accurate, but accepting a reduction in the modelling and simulation execution speed. From the point of view of 4.0 implementation, trusting also in the possibility of having an adequate ICT infrastructure, the possibilities of using wearable technologies connected to the simulation environment could be implemented. This could bring two results. The first one consists of an immediate communication between the system and the worker, who could be warned constantly about the activities to be carried out in the predetermined workplace; the latter instead concerns a continuous collection of data, to create an extensive database for subsequent machine learning applications.

ACKNOWLEDGEMENTS AND FUNDINGS

Case studies and implementations of the proposed methodology were also developed during the 'Construction Site Management' thesis workshop, academic year 2020/21. Authors: Edoardo De Santis (Eng, PhD c), Caterina Spoletini, (Eng, M.Sc.).

This work was supported by the Ministry of Education, University and Research – PRIN 2017 prot. 2017EY3ESB.

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