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CONSTRUCTION PRODUCTIVITY GRAPH: A COMPREHENSIVE METHODOLOGY BASED ON BIM AND AI TECHNIQUES TO ENHANCE PRODUCTIVITY AND SAFETY ON CONSTRUCTION SITES

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Abstract

The construction sector is characterised by distinctive issues, such as product uniqueness, the reluctance to introduce innovation, player fragmentation leading to a low productivity level and a related high level of risk intended due to the increased likelihood of damages and injuries, and the consequences on construction productivity. The common European Union regulatory framework provides strict regulations about on-site working activities, but there is still no standard for the environmental and social sustainability of construction sites. Productivity assumes a crucial role in reducing the environmental impact of construction and positively influences workers' safety due to higher levels of organisation, reducing time, costs, resource consumption and wasted time. This paper presents a methodology developed by augmenting BIM systems capabilities using Agent-based simulation techniques to simulate and optimise on-site work. The augmented BIM model allows analysis of site conditions in terms of space utilisation and resource allocation, resulting in the 'Construction Productivity Graph – CPG'. This graphic representation synthesises the results obtained, making it possible to visualise the work progression in different working areas with the resources employed, allowing for the management of productivity rates and the verification of work safety conditions.

Keywords

Project Construction Management, Agent-based modelling and simulation, Health & Safety Management, Location-Based Management, LBM, Business Process Modelling, BPM.

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1. INTRODUCTION

In light of recent geopolitical events, we are undoubtedly facing a sudden paradigm shift in the whole global production system. In the European Union – EU context, the challenges are related to the ecological transition, compromised but accelerated by the ongoing energy crisis, and a new awareness of the quality of life and social cohesion. Therefore, it is necessary to reflect on how these challenges affect the construction sector, which, among the manufacturing industry, has always had structural peculiarities and limitations that result in low productivity associated with high-risk factors [1]. The paper encompasses the research field of lean construction and health and safety management and presents a methodology for increasing productivity and the correlated reduction in risk exposure, ethical missions that point to the broader goal of process sustainability.

From an environmental perspective, construction management focuses on minimising construction-related energy consumption, which is very impactful in terms of the energy used [2]. Much of this consumption, however, is due to construction sites taking longer than expected, inefficiencies in the supply chain [3], and reworking activities because of variations, which can also result from design errors [4]. Since the 1990s, the manufacturing field has introduced lean methodologies to limit inefficiencies, but nowadays, these methodologies are not widespread. This limitation is due to structural inefficiencies in the industrial sector, such as the fragmentation of construction companies and design firms. These, being too small, do not have the economic leverage to impact production processes with investments necessary for innovation [5]. Despite this, an important diffusion of the BIM methodology, due to its collaborative vocation, allows even the smallest realities to upgrade towards digital innovation.

The efficiency of productivity in construction has a proportional relationship with the level of site safety. Notably, construction sites that are not very productive – and therefore poorly organised – physiologically have a higher level of accidents [6] because of the poor predictability of risky events in uncontrolled environments. The increase in the adoption of BIM gives the actors in the process the opportunity to use a shared database on which we can activate a whole series of data analyses that can impact the increase in productivity and, consequentially, the improvement of safety levels.

The proposed methodology relies on a BIM model linked to an Agent-based simulation – ABS environment. Therefore, each component of the BIM model is represented as an autonomous agent, which makes the model reactive to continuous design improvements and modifications, activating self-verification processes related to the satisfaction of the requirements arising from the demanding framework of the construction project. Once the characteristics of the project have been defined, the agent model activates the so-called ‘Master Actor’, who activates agents representing the work teams related to the tasks to be carried out in the assigned working area (i.e., location). The Agent system defines the duration and number of required resources based on the dynamic productivity library, which describes the task timing. The graphic result is the representation of the construction productivity graph – CPG, a synthesis of the computational processes aimed at explaining the location of tasks and the number of crews. This model shows high adaptability to changing boundary situations, with the possibility of having a quick visualisation of scenarios of the site organisation. In the current conditions, a ductile methodology can help the process’ actors manage delays or site interruptions because of health quarantines, material shortages, or the rationing of energy sources.

This paper is structured as follows: Section 2 presents the background, focusing on the advancements of lean thinking in construction, the impact of the Industry 4.0 paradigm on safety in the construction sector, and the achieved level of synergy between computer sciences and construction management. Section 3 describes the methodology and describes the development of a case study. Section 4 offers a discussion of the findings, focusing on future developments. Section 5 presents the study’s conclusions.

2. BACKGROUND

2.1. RECENT APPLICATIONS OF LEAN THINKING IN CONSTRUCTION

The lean construction approach focuses on methods and practices that aim to improve the result continuously through waste containment, respect for people, and work ethics. It achieves this by focusing on increasing productivity and quality, reducing costs, and generating maximum value. The extant literature shows synergies between the lean method and sustainable construction [7], also considering social sustainability as increasing the workers’ quality of life in construction processes, and reducing accidents at all levels.

Further insights revealed that among the various categories of methods and techniques used to implement the principles of lean construction, the most widely used practices are just in time, total quality management, and the last planner system, besides a growing interest towards agile driven by the pandemic experience, during which even a very ‘hardware’ field such as construction had to improve the dematerialisation of its production processes [8]. The growing spread of BIM has led to the development of specific prototypes, such as KanBIM, created to link BIM and lean [9]. The principal goal of KanBIM is to control workflow and visualise process parameters through 3D models in which BIM entities represent the information database. A similar product is VisiLean, another BIM–lean integration IT tool resulting from a research project [10].

However, an analysis of the comparative tests produced on these tools revealed the main issue as the link between the BIM entity and the production of the optimised process diagrams according to lean logic [11]. After 30 years of introducing these techniques, it is now possible to consider the outcomes of these methodologies. Regarding the positive ones, there is undoubtedly greater control over aspects such as space management, logistics chain effectiveness, and greater centralisation of decision-making and control processes, optimising both production times and those related to planning and change management. However, from a cognitive point of view, we can notice a possible lack of attention and responsibility by workers, resulting in a visible loss of autonomy and consequent exposure to risk in the event of working conditions that are not explicitly foreseen [12].

2.2. IMPACT OF INDUSTRY 4.0 ON HEALTH AND SAFETY IN BUILDING PRODUCTION

The construction sector is among the most accident-prone in the manufacturing field [13]. Most of these accidents result from a lack of coordination and interference at the construction site, incorrect use of machinery and equipment, and a series of human errors combined with the factors mentioned above. Not only is this problem typical of developing countries, where, for reasons also linked to a different approach to prevention, there is a high number of serious accidents, but also in the European Union [14]. From the point of view of the worksite, introducing the new Industry 4.0 production paradigm has the capacity to improve the digital connection of all the elements that make up the production ecosystem. The aim, therefore, is to transform work traditionally understood as the sequential transformation of raw materials into products according to processes of a purely mechanical nature to production managed by computerised data and the potential that these data, once inserted into management and analysis systems, can provide to forecast, production, and simulation of the results [15]. From site optimisation and safety management perspectives, it is necessary to weigh the pros and cons of this type of technology.

A current application of the Internet of Things – (IoT) technique in construction sites is the use of smart devices and wearable technologies. They have proven to be highly effective in the construction context, although there are problems with the Information and Communication Technology – (ICT) infrastructure associated with the use of these technologies. However, especially when working on buildings made of shielding materials (i.e., thick walls, etc.) or in areas that are not adequately served by broadband, there is a risk of inefficient service. This inefficiency could overestimate the positive contribution given by the system and expose the workers to underestimating the risks and correct procedures due to losing signals from the Internet of Things systems when out of the range of the data connection. A pertinent goal could be defining a standard for temporary information and communication technology infrastructure installation for construction sites to ensure continuous data exchange between real and digital environments.

2.3. COMPUTATIONAL APPROACH TO CONSTRUCTION SITE MANAGEMENT

The goal of an Agent system is to predict the emerging behaviour of the model [16]. This model is composed of agents' rules and behaviours, which are understood as the actions that enable the agent to comply with the rules and goals [17]. Of course, agent modelling is not the only way to introduce predictions into the decision-making process, as there are a series of methodologies that serve the same purpose, many of which have been tested in manufacturing and considered for the construction sector [18]. These include Discrete Event Simulation (DES) and System Dynamics (SD), which follow a top-down approach in which a system is built at the macro level at the beginning. Hypotheses are then proposed, and their validity is measured. The process is deeply based on empirical analysis and is thus affected by the implicit knowledge of the technician setting the model parameters. Agent modelling follows the bottom-up approach, in which 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 behaviour.

Another key feature of ABS is its potential to explore an efficient solution to a multi-optional problem. [19]. The ability of ABS to differentiate each individual agent leads to the generation of almost any scenario. The difference that makes ABS so close to building production lies in agent heterogeneity. Thus, whereas other simulation techniques commonly represent a system as homogeneous as well as standardised and are the properties of the elements that populate the simulation model, the ABS allows the modelling of the rules individually and verifies the behaviour of the agents both as a reaction of the individual to external stress, with the possibility of verifying how the entire system can react and coordinate during external stresses (Fig. 1). However, ABS, 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 ABS a preferable solution for activating *what-if* computational processes without relying heavily on empirical analysis, excessive assumptions, or directing the model in a preordained and biased direction [20]. Therefore, considering that ABS does not need to set rigid boundary conditions, we can test the same conditions in different environments, with clear benefits when used for H&S management [21]. This feature opens up interesting perspectives from the point of view of change management and maintenance, especially when performed during the facility's operability.

3. METHODOLOGY

The proposed methodology was developed to increase site productivity by complying with safety regulations using a sustainable approach. Both productivity and safety aspects are regulated by the efficiency of coordination and the accuracy of forecasts, so better improvement of synergies between the detailed progression of work and risk evaluations is needed. The optimisation of these aspects consents to evaluating, at a proper level of reliability, the reduction of the waste of resources from an ethical perspective of sustainability [22], due to the reduction of resources required, the diminution of time needed for the site completion, and the related decrease of emissions created by machinery and transportation of material and workers inside and outside the site. The first step to optimisation is based on a reliable model of the available areas, and related work to be performed there.

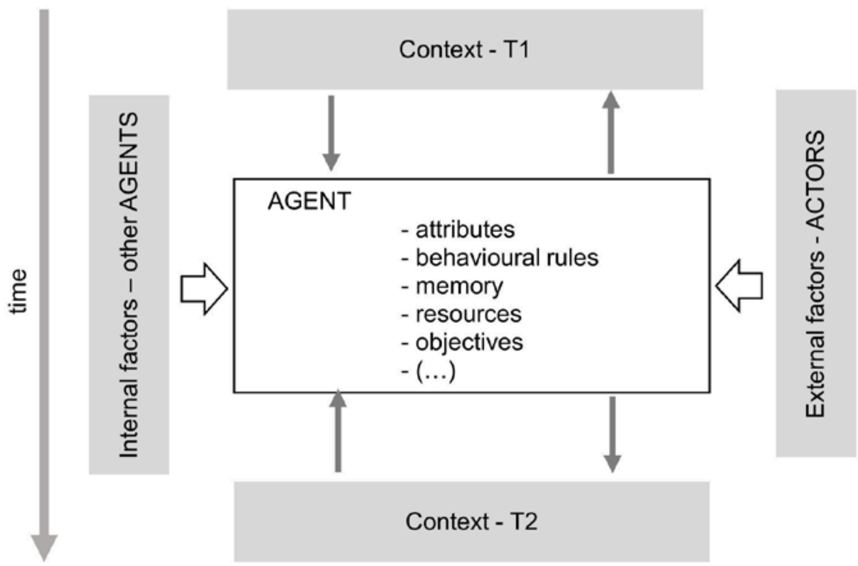

Fig. 1. *The inner structure of a simple agent.*

To address this first issue, the presented methodology uses the BIM model as a holistic box of all the components that make up a construction project.

BIM modelling for construction requires recursive checking that ensures the viability of the project itself. This implies the involvement of several design specialists who collaborate to improve design quality. To manage the level of collaboration, the fluidity of the data flow, and the speed of communications, a Business Process Management (BPM) system is presented. Thanks to the digital BPM orchestrator, this system can manage BIM data flows, activate microservices like sub-methodologies and tools activated to process a specific task, and communicate among professionals through push messages or digital file updates. Following this approach, it is possible to validate the model and obtain a viable set of building information intended as building objects. These are grouped as Work Breakdown Structure (WBS) items, corresponding to the tasks to be performed by workers in a defined location [23]. The location is the functional unit of the construction site, that is, a set of locations encompassing homogeneous work where resources can be allocated. Tasks are organised in locations by an ABS system, with the scope of maximising efficiency in using resources and considering safety regulations. Once the work to be carried out into locations has been organised, the system automatically starts checking the propaedeutic and proximity to the horizontal and vertical communication methods of the construction site to reduce wasted time and interference that may arise from the mere transit of materials through the site. Finally, the results are graphically shown overlapping a series of information, such as the occupation of the location, the crowding of nearby locations, and the productivity of the workers involved.

3.1. BIM MODEL VALIDATION PROCESS THROUGH MICROSERVICES AND DEFINITION OF RESOURCES INVOLVED

In order to guarantee the efficiency of the proposed methodology, it is necessary to gain a BIM model with an appropriate level of development (LOD) level as a reference. The proper level for these applications is LOD 400 (in the US scale, comparable to the Italian UNI 11337–LOD E), since the process flow feeds itself with the information of each element to be processed and their complex interrelationships. Therefore, the more the BIM objects are detailed, the more the data that feed the process are reliable for an ongoing and automated validation process since the early phases of construction design.

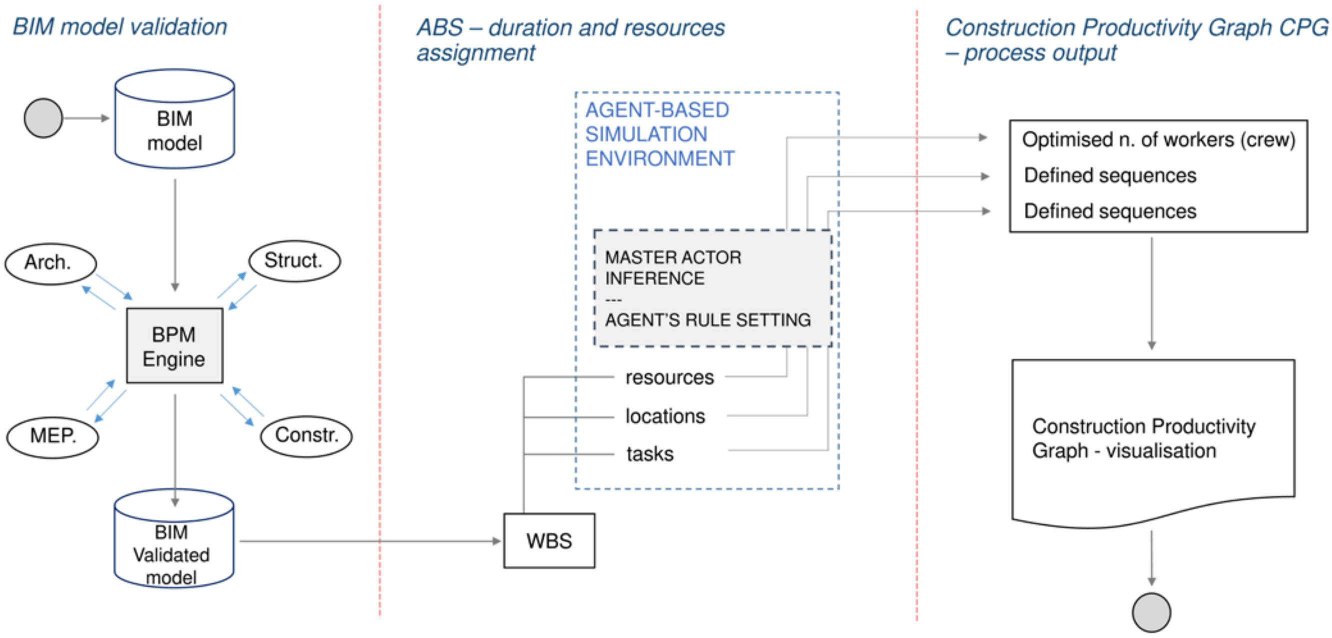

Fig. 2. *The general framework of the CPG methodology.*

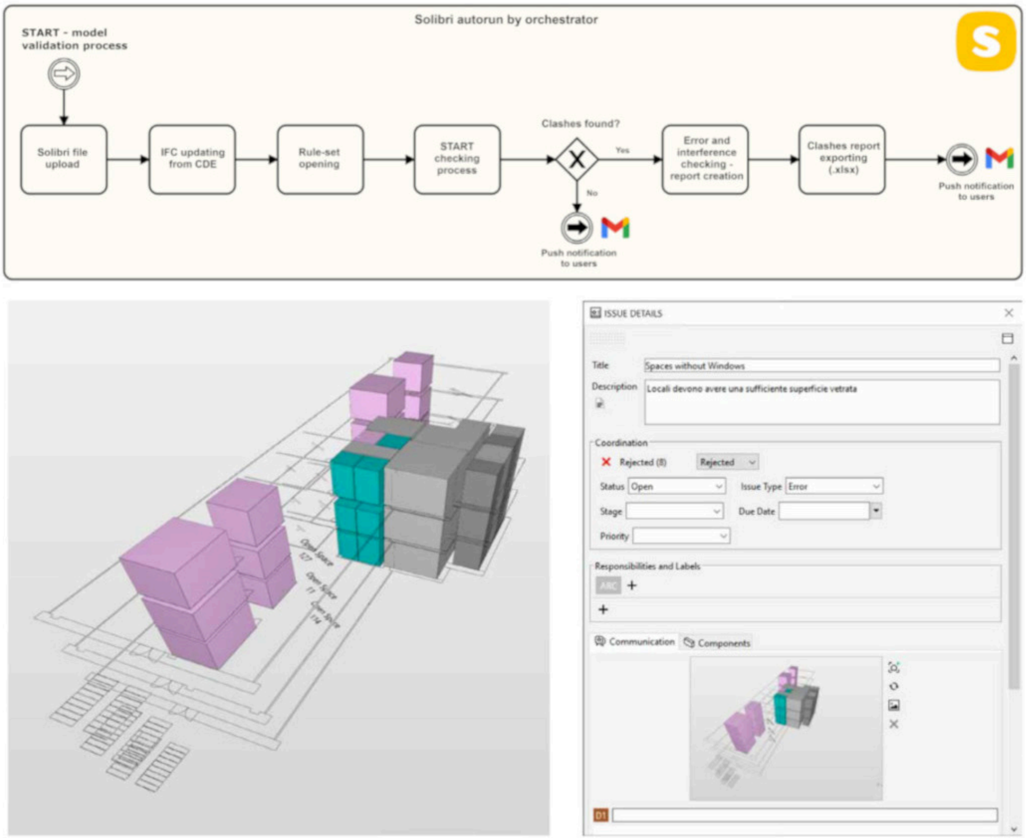

Fig. 3. *Model validation path from importing an IFC file inside a model checking tool (Solibri™). The activation of the process (micro-service) and the communication through the actor are managed by the orchestrator.*

This validation phase requires the involvement of several actors working on an evolving model. Therefore, to avoid data inconsistencies, overlapping, and low global efficiency in sharing data, it is necessary to manage this information flow inside a BPM system. It consists of a middleware system that manages the definition and orchestration of business processes [24]. To achieve our goal, we compared two approaches to BPM. The first was the use of a centralised orchestrator who gained information and sent actions to do from a unique endpoint application; the second consisted of a choreography of microservices, where data were exchanged in a circular approach but constantly supervised by the orchestrator. The workflow engine used was Camunda®, a Java-based BPM orchestrator. The results of the comparison showed that for our purposes, it was preferable to set a centralised micro-services orchestrator to clearly define the communication method among the various microservices and the actors appointed, following a 'waterfall' process framework made of consecutive validation for updating the BIM model via the direct API connection with the other microservices. For project validation, a microservice is activated (Fig. 3). The scope of the orchestrator in this phase is to manage communications and actions among the different consultants involved in the process and to monitor the completion rate of tasks.

Therefore, at this first process level, the building object to be used can be addressed, and a detailed WBS can be established. We found two main methods to develop the project WBS: the first relies on the activation of another microservices, in this case, Autodesk Navisworks®, where the designer can set a group of elements and assign them both to 4D and 5D analysis as WBS. The second method involves the use of the embedded visual programming plug-in of Revit, Dynamo®. This offers a quantity take-off organised for a group of elements representing a simple WBS activity. This method warrants direct and dynamic correspondence between the model and related quantities, raising the level of reliability and dynamicity of the analysis (Figure 04). These quantitative analyses are the basis for the development of the resource assignment phase.

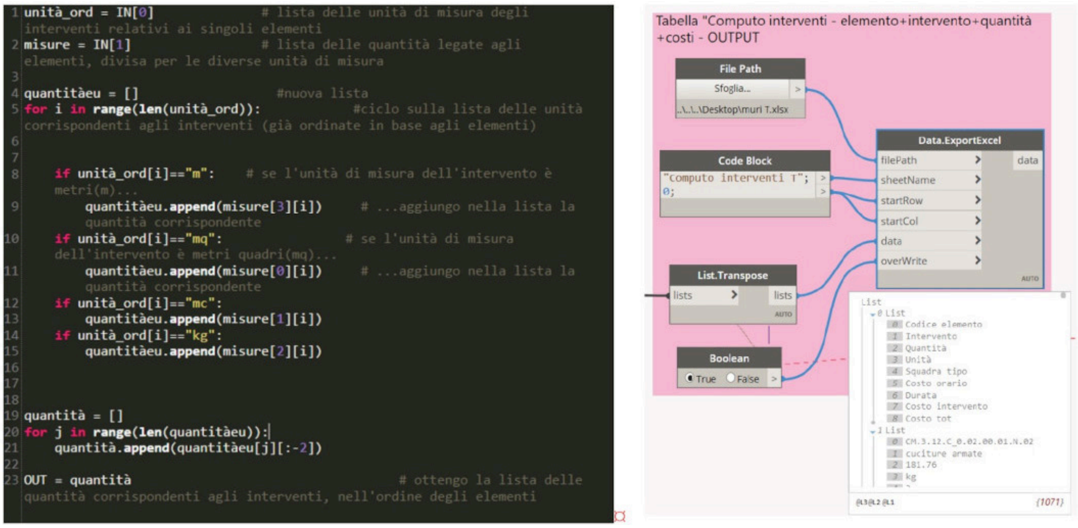

Fig. 4. *On the left is an excerpt of the script that enables the relationship between tasks and the quantities of raw material related to the building object included in the task; on the right is the Dynamo node that manages the 'task/building object/quantities/costs' *.xls output, to be transferred by the orchestrator to the subsequent process phases.*

By starting with quantities, it is necessary to account for them in relation to costs. These could be established both by public pricing indexes and by a specific cost analysis produced by the designer. These prices encompass costs related to raw materials, rental charges, company income, general expenses, and workforce costs. Thus, when the cost of the activity is known, the cost related to the workforce can be derived and divided by the imposed number of work team members, as described in the following formula:

$$T = \frac{C(A)\ x\ Wr\ (\%)}{w_t \times C\ (Dw)}$$

where:

T = time to achieve a WBS-defined activity

C = costs

A = activity, as defined in the WBS analysis

Wr = Workforce rate incidence inside the global cost of the defined activity

Wt = number of teams involved in the activity

Dw = daily wage for each worker involved in the team member, considering the different amounts related each worker's various roles and skills.

Here, it is possible to determine for each activity defined in the WBS the related time and the number of workers included in a single team, or the need to employ more than one team to accomplish the analysed activity. This development can also be useful for managing of the construction site supply chain, another important problem in terms of resource optimisation and, globally, the whole sustainability of the Construction Site.

3.2. AGENT MODEL TO ASSIGN DURATION AND NUMBER OF WORKERS TO LOCATIONS

Once the checking regarding the consistency of the model with the standards of the construction design and execution and the congruence of the WBS with the categories of work to be performed are completed, the conditions for activating of the optimised agent system for construction are addressed. This system is governed by a Master Actor (MA), who manages workflows according to the quantities and grouping rules set out in the WBS. Thus, we model the WBS themselves as agencies, that is, systems that contain other agents representing components and simple elements within them. Rules set up by the user characterise these WBS, concerning the reference location and the correct sequence for the other working phases. Precisely, the MA can send messages to agents to activate them, create temporary agents to cope with specific issues, and generally manages the cue of the agent's action or their idling status. Each process of the presented methodology starts with an MA action and is concluded by a final MA message that determines the conclusion of the process when it reaches a satisfacto-

```
/// <summary>
/// This method creates an actor for each instance of the input category inside the BIM model.
/// </summary>
/// <param name="bimCategory">The Revit category of the new actors to set up.</param>
public static void NewActorsSetup(BuiltInCategory bimCategory)
{
    switch (bimCategory)
    {
        case BuiltInCategory.OST_Doors:
            {
                // get all door instances in the model
                FilteredElementCollector bimWorld =
                    new FilteredElementCollector(Doc).OfCategory(bimCategory)
                        .OfClass(typeof(FamilyInstance));

                // extract properties and populate an ActorSetup message
                foreach (var bimElement in bimWorld)
                {
                    ActorSetup actorSetup = new ActorSetup()
                    {
                        BimElementCategory = BuiltInCategory.OST_Doors,
                        BimElementName = bimElement.Name,
                        BimElementId = bimElement.Id,
                        BimElementUniqueId = bimElement.UniqueId,
                        LocationPoint = bimElement.Location as LocationPoint,
                        ParameterSet = bimElement.GetOrderedParameters(),
                    };

                    // tell the master actor to create a child with each set of properties
                    MyMasterActor.Tell(actorSetup);
                }
                break;
            }
        case BuiltInCategory.OST_Rooms:
            {
                // get all room instances in the model

                FilteredElementCollector bimWorld =
                    new FilteredElementCollector(Doc)
                    .WhereElementIsNotElementType()
                    .OfCategory(BuiltInCategory.OST_Rooms);

                // extract properties and populate an ActorSetup message
                foreach (var bimElement in bimWorld)
                {
                    ActorSetup actorSetup = new ActorSetup()
                    {
                        BimElementCategory = BuiltInCategory.OST_Rooms,
                        BimElementName = bimElement.Name,
                        BimElementId = bimElement.Id,
                        BimElementUniqueId = bimElement.UniqueId,
                        LocationPoint = bimElement.Location as LocationPoint,
                    };
```

Pseudo-code summary of the crowd rule

```
When MA activates location ()
    Agent () append tasks in
    location ();
For each task () init workers list
    If location () is >> 1 room,
    then invoke agent (room 1, room
    2, room n ….);
    elif == 1 room then invoke
    dimension ();
    If dimension () is >= 100 mq,
    then invoke workers crew [0,1,2
    … n];
    elif << 100 mq then invoke
    workers crew [0,1,2];
For each task, if the workers crew
    >> 1, set max 20 sqm for each
    crew;
    elif workers crew ==1 set max 4
    workers/crew;
```

Pseudo-code summary of protection from falling object hazards

```
When MA activates location ()
    Agent () append tasks in
    location ();
    For each task () == [4,5,6,8]
    Then stop works in location ()
```

Fig. 5. *Parts of the ABS system: The left panel shows the creation of actors for each instance of the input category inside Revit and agents that represent rooms. On the right are two examples of rules imposed by the user.*

ry condition. Generally, the scope of the system in this process phase is to determine objects inside the model, localise and quantify them, and distribute the working teams to accomplish the works in a determined time, as explained in Section 3.1. As this phase is completed, the system starts by checking the agent's behaviour with the imposed rules, such as the crowding of locations, the risk related to the presence of workers and task-related hazards, and other rules set up by the user. The inner library of values and parameters used by the ABM system is managed by the experience of the human designer to add the implicit knowledge and experience of designers into the model and to keep contact on the effective resources available, which could be updated by a *.xls user interface linked to the agent system. This *.xls allows actors to constantly update the availability of workers, equipment, and raw materials.

The output of this iteration is the average time and number of resources that could be used to accomplish a task under the determined conditions. The results are represented in tables (Fig. 6) that link tasks, locations, and duration without graphical references. These will be automatically produced with a further automatised process, as described in Section 3.3.

Starting Date		1	2		2	3		3	4		4	5
09/11/2021 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)	Location 4 Start	Location 4 Finish
Task 1	32	9/11/21 8.00	11/11/21 13.20	32	11/11/21 13.20	16/11/21 10.40	32	16/11/21 10.40	19/11/21 8.00	32	19/11/21 8.00	23/11/21 13.20
Task 2	38	24/11/21 8.00	25/11/21 12.40	38	25/11/21 12.40	29/11/21 9.20	38	29/11/21 9.20	30/11/21 14.00	38	30/11/21 14.00	2/12/21 10.40
Task 3	105	26/11/21 8.00	30/11/21 13.00	105	30/11/21 13.00	3/12/21 10.00	105	3/12/21 10.00	7/12/21 15.00	105	7/12/21 15.00	10/12/21 12.00
Task 4	25	7/12/21 8.00	9/12/21 8.40	25	9/12/21 8.40	13/12/21 9.20	25	13/12/21 9.20	15/12/21 10.00	25	15/12/21 10.00	17/12/21 10.40
Task 5	50	10/12/21 8.00	15/12/21 9.00	50	15/12/21 9.00	20/12/21 10.00	50	20/12/21 10.00	23/12/21 11.00	50	23/12/21 11.00	28/12/21 12.00
Task 6	72	27/12/21 8.00	29/12/21 8.00	72	29/12/21 8.00	31/12/21 8.00	72	31/12/21 8.00	4/1/22 8.00	72	4/1/22 8.00	6/1/22 8.00

	5	6		6	7		7	8		8	9
Location 5 (2h)	Location 5 Start	Location 5 Finish	Location 6 (2h)	Location 6 Start	Location 6 Finish	Location 7 (2h)	Location 7 Start	Location 7 Finish	Location 8 (2h)	Location 8 Start	Location 8 Finish
32	23/11/21 13.20	26/11/21 10.40	32	26/11/21 10.40	1/12/21 8.00	32	1/12/21 8.00	3/12/21 13.20	32	3/12/21 13.20	8/12/21 10.40
38	2/12/21 10.40	3/12/21 15.20	38	3/12/21 15.20	7/12/21 12.00	38	7/12/21 12.00	9/12/21 8.40	38	9/12/21 8.40	10/12/21 13.20
105	10/12/21 12.00	15/12/21 9.00	105	15/12/21 9.00	17/12/21 14.00	105	17/12/21 14.00	22/12/21 11.00	105	22/12/21 11.00	27/12/21 8.00
25	17/12/21 10.40	21/12/21 11.20	25	21/12/21 11.20	23/12/21 12.00	25	23/12/21 12.00	27/12/21 12.40	25	27/12/21 12.40	29/12/21 13.20
50	28/12/21 12.00	31/12/21 13.00	50	31/12/21 13.00	5/1/22 14.00	50	5/1/22 14.00	10/1/22 15.00	50	10/1/22 15.00	13/1/22 16.00
72	6/1/22 8.00	10/1/22 8.00	72	10/1/22 8.00	12/1/22 8.00	72	12/1/22 8.00	14/1/22 8.00	72	14/1/22 8.00	18/1/22 8.00

Fig. 6. *The output of the agent-based simulation showing tasks, locations, and time needed.*

These duration analyses are critical for the management of time and resource optimisation, given that a large part of the optimisation conditions derives from the possibility of using a date number of locations in parallel, managing interference and the possibility of using shared logistical conditions to reduce the areas of transit and handling of loads on the site, conditions characterised by a high risk of accidents. This activity also helps in the evaluation of the wasted time of transport within the site; thus, the goal is to maximise the work planned in areas close to the loading verticals and horizontal handling paths on the floors.

3.3. LOCATION AND CREW VISUALISATION

Once the number of workers is obtained from the ABS in relation to the work to be carried out for each location, a new microservice is activated for the graphic visualisation and checking of interference in relation to the activities expected for each location and the number of workers used. Simple spreadsheets in accessible and widespread formats, such as *.xlsx, were used to define these graphs. In the first part of graph development, the location-based structure (Fig. 7) is set up so that the duration of work, the maintenance of the optimal workflow average [25], and any overlaps can be fully visualised.

The first graphical result (Fig. 8) combines the graphical ease of the Gantt diagram with the staff presence line graph. This representation, which is unique for each location, makes it possible to verify both the sequence of activities (Gantt) and the simultaneous presence of people (line graph), to monitor the crowding of areas, any issue related to the activities and the number of workers present, and to constantly verify the adequacy of worksite facilities (e.g., toilets, canteens, etc.) in relation to workers' expected number. This kind of representation is the output of CPG. Once the congruence of data of the individual locations has been verified, the results related to the entire worksite are inputted into the system for a complete overview of the optimised consecutiveness of the works.

We represent these according to the Gantt technique, whereas the line graph shows the co-presence of workers. This analysis verifies the worksite and areas' occupancy rate, and the most critical one is analysed. From a conceptual point of view, this graphical methodology is a decomposition of the well-known location-based management technique, which, displayed in another view, allows a constant overview of productivity and the occu-

```
LBM_DB - 1

Sub LBM_DB()

    Dim L, T As String
    Dim i, j, NLocations, NTasks, NTeams As Integer

    Worksheets("Locations Table").Activate
    Range("A2").Select
    NLocations = Range(Selection, Selection.End(xlDown)).Row
    Worksheets("Tasks List").Activate
    Range("A2").Select
    NTasks = Range(Selection, Selection.End(xlDown)).Rows.Cc
    Range("B1").Select
    Worksheets("Teams List").Activate
    Range("A2").Select
    NTeams = Range(Selection, Selection.End(xlDown)).Rows.Cc
    Range("B1").Select
    Worksheets("LBM Database").Activate
    Cells.ClearContents
    With Cells.Interior
        .Pattern = xlNone
        .TintAndShade = 0
        .PatternTintAndShade = 0
    End With
    For j = 0 To NLocations - 1
        Cells(2, 3 * j + 2) = Worksheets("Locations Table").
        Cells(1, 3 * j + 3) = Worksheets("Locations Table").
        Cells(2, 3 * j + 3) = Worksheets("Locations Table").
        Cells(1, 3 * j + 4) = Worksheets("Locations Table").
        Cells(2, 3 * j + 4) = Worksheets("Locations Table").
    Next
    Rows("2:2").Select
    Selection.RowHeight = 30
    With Selection
        .HorizontalAlignment = xlCenter
        .VerticalAlignment = xlBottom
        .WrapText = True
        .Orientation = 0
        .AddIndent = False
        .IndentLevel = 0
        .ShrinkToFit = False
        .ReadingOrder = xlContext
        .MergeCells = False
    End With
    With Selection.Interior
        .Pattern = xlSolid
        .PatternColorIndex = xlAutomatic
        .ThemeColor = xlThemeColorAccent4
        .TintAndShade = 0.6
        .PatternTintAndShade = 0
    End With
    With Rows(1)
        .HorizontalAlignment = xlCenter
        .VerticalAlignment = xlBottom
    End With
    Range(Columns(2), Columns(NLocations)).ColumnWidth =
    Sheets("Tasks List").Select
    Range("B2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Range("B1").Select
    Sheets("LBM Database").Activate
    Range("A3").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False
    With Selection.Interior
        .Pattern = xlSolid
        .PatternColorIndex = xlAutomatic
        .ThemeColor = xlThemeColorAccent5
        .TintAndShade = 0.6
        .PatternTintAndShade = 0
    End With
    Columns("A:A").EntireColumn.AutoFit
    Cells(2, 1).Select
    ActiveCell.Offset(-1, 0).Value = "Starting Date"
    ActiveCell.Value = Date + 8 / 24
    ActiveCell.NumberFormat = "dd/mm/yyyy h.mm;@"
    With Range("A1:A2")
        .Borders(xlDiagonalDown).LineStyle = xlNone
        .Borders(xlDiagonalUp).LineStyle = xnlNone
        .Borders(xlInsideVertical).LineStyle = xlNone
        .Borders(xlInsideHorizontal).LineStyle = xlNone
        With .Borders(xlEdgeLeft)
            .LineStyle = xlContinuous
            .ColorIndex = xlAutomatic
            .TintAndShade = 0
            .Weight = xlMedium
        End With
        With .Borders(xlEdgeTop)
            .LineStyle = xlContinuous
            .ColorIndex = xlAutomatic
            .TintAndShade = 0
            .Weight = xlMedium
        End With
        With .Borders(xlEdgeRight)
            .LineStyle = xlContinuous
            .ColorIndex = xlAutomatic
            .TintAndShade = 0
            .Weight = xlMedium
        End With
        With .Interior
            .Pattern = xlSolid
            .PatternColorIndex = xlAutomatic
            .ThemeColor = xlThemeColorAccent3
            .TintAndShade = 0.6
LBM_DB - 2

            .PatternTintAndShade = 0
        End With
    End With
    With Range(Cells(NTasks + 5, 1), Cells(NTasks + 5, 2)).Int
        .Pattern = xlSolid
        .PatternColorIndex = xlAutomatic
        .ThemeColor = xlThemeColorAccent6
        .TintAndShade = 0.6
        .PatternTintAndShade = 0
    End With
    Cells(NTasks + 5, 1) = "Teams Name"
    Cells(NTasks + 5, 2) = "Members"
    Sheets("Teams List").Select
    Range("A2:B2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Range("B2").Select
    Sheets("LBM Database").Activate
    Cells(NTasks + 6, 1).Select
    ActiveSheet.Paste
    Application.CutCopyMode = False
    Cells(NTasks + 6, 3).Formula = "=+A2"
    Cells(NTasks + 6, 4).Select
    For j = 0 To NLocations - 1
        L = Worksheets("Locations Table").Cells(j + 2, 2).Valu
            For i = 1 To NTasks
                T = Worksheets("Tasks List").Cells(i + 1, 2).\
                Cells(i + 2, j * 3 + 2) = Worksheets("Tasks Pi
            Next
        Next
End Sub
```

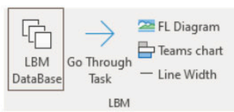

Fig. 7. *Source code for plotting the productivity graphs.*

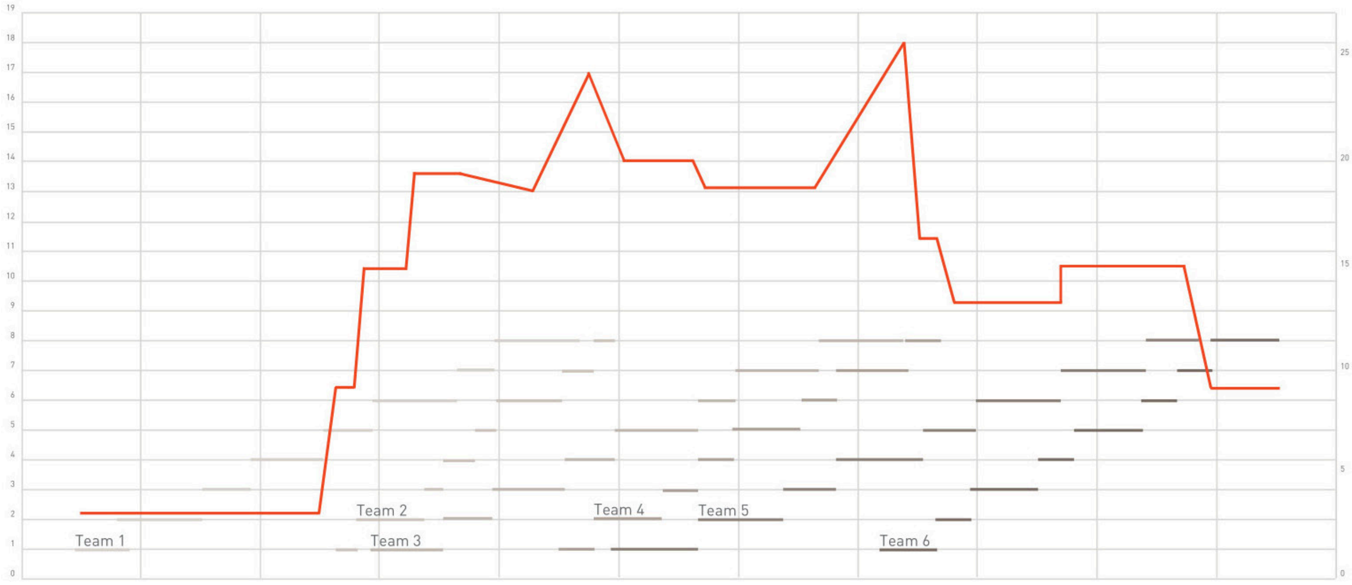

Fig. 8. *A construction productivity graph: The red line shows the number of workers; the greyscale lines show the tasks; The teams involved are also shown. Analysis conducted for a single location.*

Fig. 9. *An extended view of CPG line of balance, derived from the ABM process.*

pancy of working areas (Fig. 9). These in-depth process services are linked to the BIM model, which, thanks to the continuous exchange of data made possible through the API, updates the technical elements displayed at each stage, thus having a bi-univocal link between the graphic representation of the production processes and the construction site BIM model.

4. CONCLUSION AND DISCUSSION

The proposed methodology faces the strictly related efficiency and sustainability construction sites' request. The papers present a methodology that grounds on BIM, BPM and ABS that allows to define a system able to define processes finalised to improve efficiency and sustainability. The methodology produces a BPM process that starts from a BIM model that contains information for CPG definition. The BIM model data are validated through the involvement of checking tools and involved specialists, automatically activated by a BPM network. An ABS system uses validated information to define the resources to employ to accomplish working tasks. The final balanced results are represented in overlaid graphs that describe the location crowding, the productivity of workers' crew and, globally, the construction management metrics. This information flow, guaranteed by the

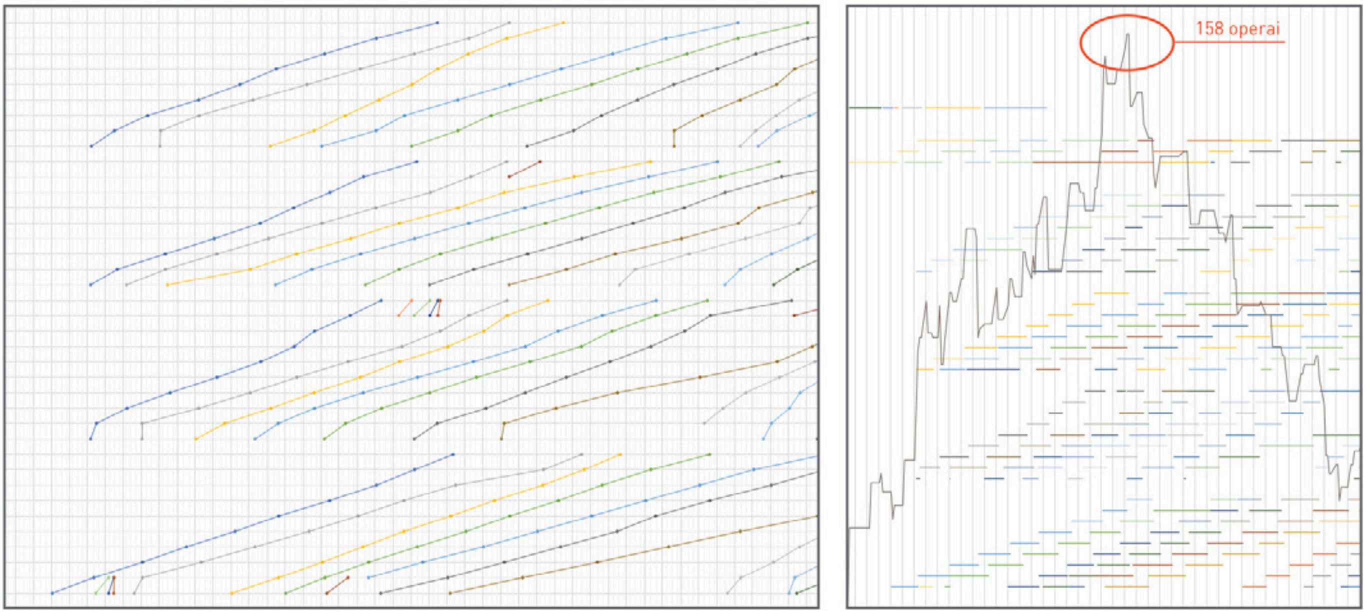

Fig. 10. *An overview of the line of balance of the site and the issue highlighted in the productivity graph.*

service orchestrator and managed via APIs, opens interesting perspectives of the further method's evolutions. Thus, other microservices could be added to the workflow to make the results increasingly accurate while accept a reduction in the modelling and simulation speed of execution. From the point of view of Industry 4.0, wearable technologies connected to the simulation environment could be implemented. This could have two results. The first comprises immediate communication between the system and the worker, who could be constantly warned 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.

The results' efficiency and accuracy depends both from on the LOD level and the BIM model, and also from the completeness of rules' definition inside the ABS environment. Considering that LOD is referred to an object and not for the whole model, this methodology could face inaccuracies if the model were populated by building objects with a lower LOD level than necessary because of the possible lack of information required to excerpt reliable quantities and tasks' details. However, the methodology reserves particular attention to offering users an easy and ready-to-use interface, providing results in a usable standard *.xlsx dashboard for inputting data and read outcomes. From the point of view of safety this methodology allows for better coordination of the presence of workers and the crowding of areas. For example, in the case study, due to the methodology implemented, we observed an underestimation of the productivity reduction factor due to peak occupancy and overcrowding in some areas that are also at high risk, such as the roofing structures (Fig. 10).

Considering the analysis of the background, the CPG could be fully integrated into lean methodologies for the capability to save time and resources through organisational improvements, such as the better definition of resources required, which reflects a more efficient supply chain to reduce wasted time, occupancy of site soil to host waiting material, and the logistic impact within the site and on the neighbourhood. Furthermore, these aspects reflect a lower pollution production because of the shorter duration of site operation and a smaller impact on urban mobility, where sites are located inside urban centres. Finally, in view of these findings, the following issues present opportunities for future work:

- 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 relatively quickly. It could be interesting to evaluate the development of digital meta-models, which will show representative values of the project, in order to carry out rapid assessment, creating a new design level named 'constructive feasibility'.

- Forecast accuracy: For 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 face many practical obstacles, since the construction plans of construction sites, execution methods, and metrics of realised projects could be classified proportionally to the intended use of the building itself and sometimes problematic to share (e.g., justice facilities and airports). Similarly, it is difficult to create a shared common data environment from the point of view of the production process of construction companies, which have part of their capitalisation and value in the construction and maintenance of best practices and standardised procedures. Therefore, 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 the information necessary to train data libraries dedicated to the construction elements of the building, and the related agents and rules.
- Auto-generative knowledge: An interesting research effort would be to gather the experiences gained on the building site itself as a basis for improving the decision-making process for the following construction phases. This could allow for solving the need to manage a knowledge strongly related to a single case, as experienced in building construction.

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Authors contribution

The authors both participated equally in writing the article.

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