The Future of Construction in the Context of Digitalization and Decarbonization

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A FRAMEWORK PROPOSAL FOR CONSTRUCTION SITE AGENT-BASED SIMULATION

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ABSTRACT:

Construction sites are complex and dynamic environments where the continuous mutual interactions among a sheer number of entities (e.g. workers, machines, equipment) and activities determine the frequent occurrence of unpredictable hazardous events that makes risk estimation one of the most challenging tasks of Health & Safety (HS) management. In recent years, the growing adoption of Building Information Modeling (BIM) and Internet-of-Things (IoT) supported HS Managers in the improvement of construction site planning and monitoring and hence increased workers' safety. Nonetheless, probabilistic estimation of hazardous events and related risk estimation still heavily relies on HS Managers' field experience. This contribution proposes a novel framework for the adoption of an Agent-Based Modeling and Simulation approach integrated with BIM in a game engine environment for the probabilistic estimation of collision events in construction sites, between workers and heavy vehicles. The paper provides the definition of the hazardous event occurrence and discusses in detail the main aspects of the framework, including: the use of BIM data to create the simulation scenario, the agents and the rules that drive their behaviors. The presented framework is the first part of an ongoing research that will comprise its implementation and application in case study.

KEYWORDS: *Probabilistic hazardous event estimation, Construction site planning, Agent-based Modeling and Simulation, Building Information Modelling (BIM), Health & Safety management.*

1. INTRODUCTION

Due to the dynamic and constantly changing nature of the construction site and many different types of entities that live it, we can consider the site environment a complex system. Construction is often the largest source of employment in any country and AEC projects such as buildings, infrastructure systems and plants are part of the scope of urban spatial planning and design and have an immediate impact on and a direct relation to the accommodation of land use for the future growth of cities. However, the construction sector still presents today critically in terms of safety and accident, despite the continuous updating of prevention regulation and the adoption of new technologies. Safety management is a fundamental part of the construction process and must begin at the design stage through the site-layout design and safety measure to be adopted. The success of the project lies in the effective ability to respect the construction schedule in terms of time and costs, and it depends for great part on the construction site choices, carried out in planning phase because of risk estimation. Data recorded by the National Institute for Insurance against Accidents at Work (INAIL), which carries out activities of prevention and safety of the workplace in Italy, shows that the construction sector is the most dangerous work sector, with 27% of work-related deaths, where among the most frequent occurrence modes results in interaction with equipment/Machine, of which more than 50% caused by the activity of the injured person and by structural and organizational deficiencies of the workplace, which in this case are the sites. These results are also found in other countries, for example Occupational Safety and Health Administration (OSHA) reports that the second cause of fatalities in the construction industry after falling is struck-by from heavy equipment (Vahdatikhaki & Hammad, 2015). So the presence of dynamic resources such as heavy equipment, vehicles and materials, that works in proximity to ground workers can cause hazardous situation, increasing the risk of injuries and fatalities for construction personnel (Marks & Teizer, 2013). Many studies investigated the hazardous proximity and collision issues, on one hand with optimizing planning and scheduling methods that consider the space requirements of various activities to avoid the dangerous proximities among different team of equipment (Chavada et al., 2012)(Moon, Kim, et al., 2014), on the other hand with the application of new real-time proactive detection and alert technologies to mitigate the collision risks by warning the workers from potential hazardous events (Teizer & Cheng, 2015). Moreover, the new research trend aims at using of BIM-based simulation to improve the construction site planning, monitoring, and risk management to increase the safety of workers in the construction site. This contribution proposes a novel method to predict these hazardous events at the site-design phase, through an Agent-Based Simulation of the activities implemented in a game engine (Unity 3D), from the data contained in a 4D BIM model. So, with the creation of a 3D digital scenario of the construction activity and its simulation, from the interaction between the site entities and the representation of hazard spaces, it is possible record the collisions between them occur during the simulation. The goal of the research is to provide a map of the proximity hazardous events that can suggests to the safety manager how to act in terms of layout design and activities planning to eliminate that risk.

2. BACKGROUND

Over the last few years, with the rapid development of new tool and Information technologies, the world of research has shown considerable interest in their application to the field of Construction. BIM concepts, new simulation methods and the use of game engines have seen a significant increase in their adoption for the safety management of workers on site. Below, a description of the issues emerging from the research regarding these aspects is provided.

2.1 BIM AND HS MANAGEMENT

Utilizing BIM and BIM-related digital technologies to manage worker safety has been a growing research interest in the AEC industry. Most studies, classified within this research trend, are based on the development of a knowledge-based system for safety management integrating a BIM platform, because every project produces valuable knowledge and experience which can contribute significantly to managing risks in future projects with the help of BIM. For example has been developed a tool for assessing construction risks during early phases of multistory building projects at an activity level and on a daily basis in a 4D environment (Jin et al., 2019). Other example focuses on the requirements for defining a database of construction hazards to be implemented in a BIM environment (Mihić et al., 2018). In another study aim to reduce the theoretical gap between knowledge and experience proposing a tailored Risk Breakdown Structure (RBS) for a BIM-based risk management framework for bridge projects (Zou et al., 2016). A much-analyzed topic concerns the verification of the project through rule checking based on BIM model. In some cases they focus on the development of rule checking systems and tools starting from BIM models (Schwabe et al., 2019), proposing the development of a rules-checking interface that works through construction site layout objects in Building Information Modeling (BIM) and the construction schedule (Schwabe et al., 2016). Other work demonstrates the potential of the approach, focusing on individual specific risk situations, such as falling from a height. (Zhang et al., 2015).

There are also contributions from the more managerial aspects where methods for the digitization of the HS normative text for construction site are studied and illustrated, from the interpretation of the rules to the creation of the set of parametric rules that can be implemented in the BIM library of the construction site, so as to translate BIM objects into effective design control tools to support the safety manager in the design and drafting of a safety plan compliant with the standard (Getuli et al., 2017). Another aspect emerging from the research concerns the creation of 4D BIM virtual prototypes as models for the simulation of the construction process, to provide the safety manager with data and analysis tools in the planning phase to support him in his decision-making process(Zhou et al., 2013)(Tak et al., 2021). Particular attention was shown to the optimization of site spaces and the planning of the schedule of activities, minimizing spatial conflicts through the simulation of site activities through 4DBim models (Moon, Dawood, et al., 2014).

In recent years, moreover, the development and adoption in the AEC world of new visualization and simulation technologies such as VR and AR, has seen the integration of BIM and Game Engine models. These technologies are mainly used for construction education and training of worker about construction site activity and organization (Getuli et al., 2018)(Getuli et al., 2020), for which smart object libraries have also been studied and proposed for BIM models on construction sites to support training experiences on safety in the VR environment (Getuli et al., 2022). The potential deriving from the integration of BIM and Game Engine models has also been exploited during the monitoring phase of the construction phase, such as for example for the automatic updating of the 3D BIM model through the real-time acquisition of images of the site's statuses, so as to provide project managers with an advanced decision-making tool that highlights in real time and effectively the inconsistencies between construction and planning (Pour Rahimian et al., 2020).

2.2 AGENT-BASED MODELING AND SIMULATION

Recent advancements in the development of computer simulations supported by increased computing power have led to the emergence of simulation and modeling techniques that resemble actual systems more accurately, and agent-based modeling (ABM) is one of these powerful simulation modeling techniques. This method has seen the involvement of all phases of the building process, in particular the applications of ABM to solve problems relevant to the construction phase. The strength of ABM in simulating site activities has been confirmed by the literature and it has been utilized by many studies to improve equipment operations on construction sites, also from the point of view of the safety of operations (Marzouk & Ali, 2013) (Younes & Marzouk, 2018). Moreover, given the close link between the safety of the work and the productivity of the construction site, and considering as central the role of the safety of workers and work teams for the success of a project, Agent-Based Model and Simulation has been adopted by more studies to model the behaviour of construction laborers, crews and their interaction considering the social-cognitive concept (Goh & Askar Ali, 2016) (Binhomaid, 2019). In addition to academic research, the diffusion of this simulation system is also due to the the growing number of ABMS-specific software that can be used in combination with common and widely used building information modeling (BIM) and computer-aided design (CAD) platforms. In general, the goal is always to verify the design choices by simulating through ABMS the behavior of the occupants and their response within the virtual environment, in relation to the different types of situations, such as evacuation in emergency conditions in complex environments such as a construction site (Marzouk & Daour, 2018) or a conference hall (Bina & Moghadas, 2020).

3. RESEARCH FRAMEWORKS AND METHODOLOGY

Complex systems are systems where the collective behaviour and the interactions of system entity entails emergence of properties that cannot be explained by the understanding of the individual components only. The study of complex systems investigates how that interactions and relations between single entity can form overall structure and exhibit collective behaviour (Stieler et al., 2022). The construction site can be considered a complex system as characterized by many activities, often contemporary and overlapping where several types of autonomous entities interacting with each other lead to events difficult to predict also, especially in safety aspect.

Agent-based modelling and simulation is an approach to model these complex systems to understand the emergence of these events. So, the Aim of the present contribution is to build a novel framework for the introduction of an Agent-Based Model Simulation evaluation approach of the conflict between worker and equipment in the construction site during activities, to estimate the probability of occurrence of the hazardous event of contact between workers and heavy vehicles. The idea is based on the implementation of the virtual simulation environment using the 4D BIM models of the project and construction site and the related data. These allow the creation of a virtual scenario for a specific moment of time (phase n) corresponding to a given configuration of the construction site. Through the schedule it is possible to easily identify the planning data related to the specific activity and link them to the BIM object concerned, the data on the type and quantity of human resources and heavy vehicles useful for identifying and loading into the simulation the 3DObjects corresponding to the agents of this virtual scenario. Finally, by choosing a method for the representation of danger zones and for the detection of collisions between human resources and these zones, the rules that will govern their behavior in terms of navigation are defined and correlated to the agents. In this way it is possible to simulate the movements of machines and workers within the virtual scenario and record the interactions between the danger zones of the equipment and the workers themselves.

The goal of the simulation is to make a predictive estimate of the probability of occurrence of the investment risk or contact with heavy vehicles by recording the number and position of collision events that occurred between the agents during the simulation. That approach introduces Artificial Intelligence-based Simulations of construction sites' dynamics to support decision makers to predict these situations and suggest actions for the optimization of the safety at level of site layout and activities planning. The framework development (Fig.1) consists of four main components, 1) Defining and preparation of input data, 2) Implementation of simulation scenario, 3) Recording and processing of simulation data, 4) Decision-making support to the Safety Manager. The first three parts, described below, consists in the core of the study, and allow you to provide the data for the fourth part, which is to support the safety manager in checking his choices and eventually identify the most critical situations where there's the need for a redesign at level of site layout and schedule.

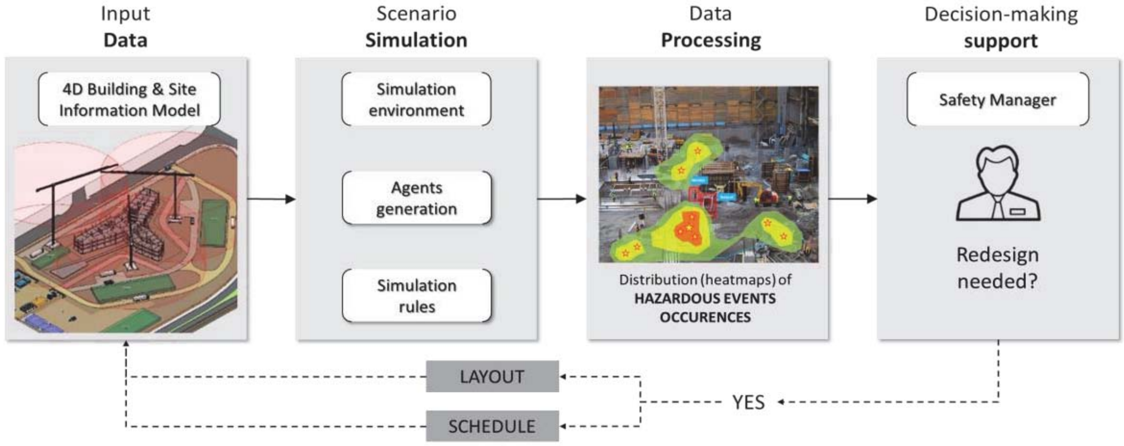

Fig. 1: Framework for activity Agent-Based Modeling and Simulation

3.1 DEFINITION AND PREPARATION OF INPUT DATA

The starting point of the process are the Building Information Models being the container of the design and planning information. For this reason, it is necessary to acquire the following input data (Fig.2):

1) The BIM design model comprehensive of all building elements eventually arranged in multiple mono-disciplinary models provided from different firms (architectural, structural and MEP).
2) The BIM site layout model which must comprise of at least the facilities (different type of space) and static equipment (fences, parapets, scaffolding, ramps, …) corresponding to the construction activities.
3) The construction schedule containing the remaining information related to the time and resource planning of each construction activity.

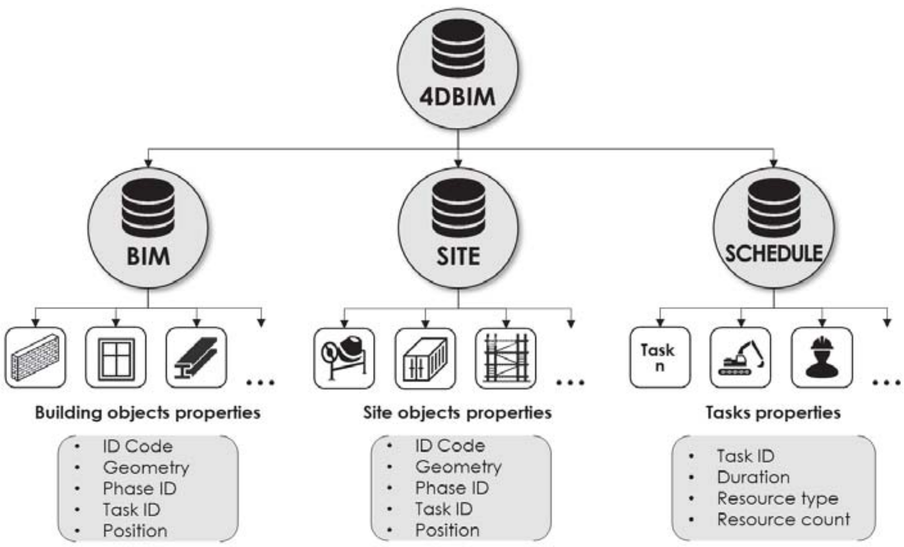

Fig. 2: Models structure and related input data

First these BIM models provides geometric data (e.g. length, width, and height) of each building elements such as structural elements, architectural element, system elements and site layout elements as well as their location data (geographic position) inside the reference system of the model, useful for the construction of the 3D virtual simulation environment. However, such data aren't enough to identify the real different configuration that the site layout will assume during the construction progress. In fact, in relation to the development of the construction object, we can observe the presence or absence of different elements which implies a different space and equipment organization, corresponding to different layout configurations. A significant example of this layout configurations can be seen in the clear differences that are found between the excavation phase, the construction of the structural part and the installation of architectural elements. It is therefore necessary to generate a federated model of coordination organized by phases, consisting of the linked models of all disciplines. A structuring of the model in phases involves the organization of the different models according to the different macro-configurations of the construction site, within which all the project and construction site components are distributed according to phases corresponding to the different site activities. This organization is achieved by enriching each BIM component with a first parent parameter (Phase ID), corresponding to the site configuration, and a second parameter (Task ID) corresponding to the code of the work package from WBS of the different categories of objects. The first data is useful as filtering during export of the model for the creation of the n simulation scenarios corresponding to the macro-configurations of the construction site. Instead, the second parameter will allow the management of the various components, site, and project, within the simulation scenarios, as well as their connection to the relative schedule data (duration and resources data). In this way we created a 4D BIM model that allows to build the correct simulation scenario, with the geometric data of project and construction site elements distributed to the different activities provided by scheduling, as well as those data that allow the implementation of not model elements, within the simulation, such as human resources and eventually dynamic equipment which represent the so-called simulation agents. Data exchange and interoperability between the BIM software and simulation software required a standard for transferable data which interest us. For these reasons it was chosen to use the IFC opens source format, which allows the interchange of properties, relationship, and semantic information of the BIM model. In this case the IFC 4 version allows us to correctly map not only the geometric information of the 3D BIM model but also the information related to the construction process contained in the 4D BIM model, that is task data and resource data, through the schema ifcConstructionMgmtDomain and ifcProcessExtension.

3.2 IMPLEMENTATION OF SIMULATION SCENARIO

Agent-based modelling and simulation is an approach for the movement of complex systems composed of autonomous and interacting agents (MacAl & North, 2010). Agents are endowed with an intelligence or rather a behavior described by rules, which allows them to interact with other agents and with the environment. The heart of an agent-based approach is precisely the autonomy of agents through a series of rules of behavior that allow them to question the environment on which they act, make decisions, and carry out actions according to the continuous perception-decision-action cycle. Generally the context environment is passive and the phenomenon of use emerges from the combination, iteration and interference between the agents (Simeone et al., 2017). In this contribution, the agent-based approach must study the construction site system during the performance of a schedule activity where, different types of agents navigate the environment according to rules of behavior interacting with the environment and the agents themselves. The overall aim is to record and map specific hazardous events that occurred during the simulation, for hazardous events we mean the interactions in terms of collisions between the different specific types of agents, to be able to provide data on the quantity and position of these events within the construction site. The usefulness of such data is to provide support to the safety manager in identifying preventive measures at the level of layout and planning of activities for the resolution or mitigation of risk (investment, contact with moving parts, crushing, etc.).

There are many specific platforms for Agent-Based Modelling and Simulation, few of which have included 3D features, most of which allow the development of two-dimensional models. In recent years other types of platforms such as Game Engines, thanks to their advanced 3D graphic support and a user-accessible programming interface for the implementation of the logic of the game model, allow the implementation and development of 3D Agent-Based model and simulation. Typical game engines are composed of several main parts, including a rendering graphics engine for 2D and 3D models, a physics engine for the implementation of laws of kinematics and dynamics (movements, collisions, etc.) as well as graphical interfaces for model management and scripting. The most powerful and most widely used game-engines on the market are essentially three, Unity3D, Unreal Engine and Blender. For this work we chose the use of Unity3D game engine because 1) it is equipped with an Open-source version, 2) it has been widely used as a simulation implementation platform, 3) it has a very powerful graphic and physical engine, 4) it has an official asset store where you can download different resources and features already created by other developers, to be used in your project.

Therefore, a typical Agent-Based Model is characterized by three fundamental elements 1) Simulation environment, 2) Autonomous agents, 3) Simulation Rules, rules that manage the behavior of the agent and the simulation. Below these elements will be analyzed with reference to the objective to be pursued. As already mentioned above, the construction site can be considered as a complex system, as it is characterized by many work activities, often overlapping and interfering, in which different types of entities are present and act. Before the development of the Agent-Based model, a classification of the site entities for this specific case was necessary, so from the analysis of several real construction site environments the following classification was proposed (Fig.3):

- Entities without intelligence: Static elements, which constitute a fixed or temporary obstacle in the construction space and play a passive role in the construction activity.
    - Built elements, have been object of construction activities in previous phase, that occupancy permanently space on site.
    - Under construction object, they are the subject of ongoing construction activities, determining the permanent and increasing occupation of a certain space necessary for its construction.
    - Static equipment: installed or stored during the phase, they can change position/configuration only if moved or handled.
- Entities with intelligence: Dynamic elements, which contribute to the performance of the work activity possibly also using static entities.
    - Workers that they move within the construction site in correspondence with the work area of competence and between the construction site areas not always following predetermined paths and according to a logic of need.
    - Dynamic equipment: they move within the construction site in correspondence with the work areas according to the activities to be carried out (excavation, transport, loading / unloading, material handling, etc.).

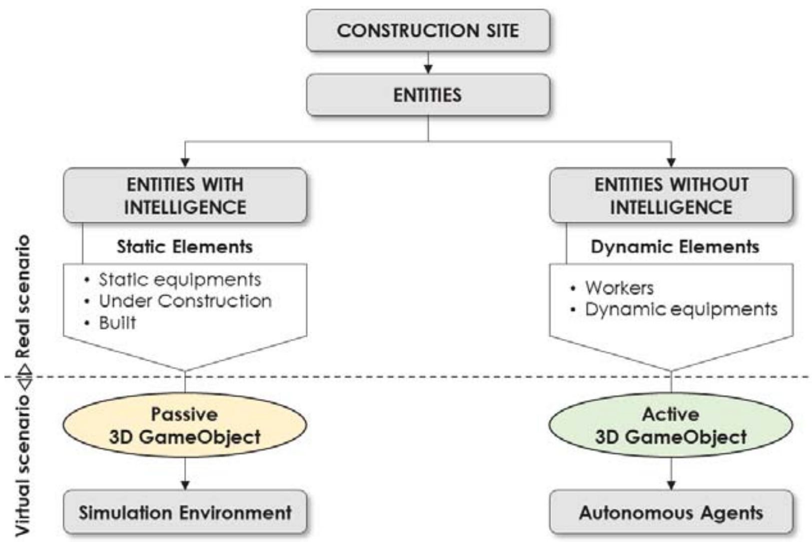

Fig. 3: Site entities classification for Agent-Based Modeling and Simulation construction activities

3.2.1 Simulation environment

The simulation environment is created using the 3D BIM model of the project of the various disciplines and the 3D BIM model of the construction site. Each model must serve to transfer the three-dimensional geometric content of all the modeled entities within the game engine, these entities will therefore represent the GameObjects that will constitute the context environment that will be "lived" by the simulation agents. Through the export of the phased model in iFc format we have the file in open format that can be imported into Unity. Unless you use specific paid tools that can be downloaded from the Unity Asset Store, the correct import of the IFC file and the information content of the elements requires a slight manipulation of the file itself. This format, in fact, to be correctly readable by the game engine needs to be converted into two types of formats and processed by script, .OBJ for the import of geometries and .XML for the import of their information content. In this way the BIM models and all its entities are usable for the creation of the simulation scenario.

Once all BIM objects related to a given phase and work package have been imported as 3DGameObject, they must be made an active part of the scene through the implementation of their physical properties. In particular, the surfaces that can be traveled by workers and machinery, such as the construction site ground, ramps, parts of static work equipment, must be made navigable by our agents. In addition, agents during navigation must reflect the real behavior of machinery or workers in motion, or search for the shortest route among the possible construction site routes avoiding fixed obstacles voluntarily, without colliding with them. The correct procedure to do this is the creation of the NavMesh of the walkable surfaces by defining the static entities as

NavMeshObstacle, in this way the agents can move by calculating the shortest path (using A*Algorithm used by the function) on the real navigable surface, voluntarily avoiding the collision with fixed obstacles instead of after colliding. In addition, the NavMesh component can be updated in relation to the appearance of new static elements on the scene, using scripts that invoke the function SurfaceBuildNavMesh. This is very useful in our case, as it allows you to modify the navigable surfaces in relation to the appearance of the entities related to the different work packages of each task from the schedule, for example during the installation of steel pillars of a certain level of the building, the pillars are not all laid at the same time, in the initial situation I will find an environment without pillars and every time a pillar is installed, even if the construction site configuration remains the same, the environment changes as there is a new obstacle that will modify the navigable surface by the agents during the same activity.

3.2.2 Autonomous agents for Agent-Based Modeling and Simulation of construction activities

The real scenario of each phase of work is therefore composed either by static entities that play a passive role in the simulation, which constitute our simulation environment and treated as indicated in 3.2.1, and dynamic entities that move between the static entities according to specific navigation behavioral logics. In a gaming environment, this type of agent is generally defined as Non-Player Characters (NPC), or the characters of the game that have an autonomous behavior, that is, not moved by an intelligent resource such as a human can be, but from its AI system that allows it to make decisions. Therefore, these entities need a representation in the simulation scenario in the form of 3DObject with additional physic properties, this way I have on one hand the static entities will constitute the navigation environment and the obstacles as well as the targets for the navigation of the dynamic entities, on the other hand dynamics entities through the implementation of rules and navigation logics are transformed into the so-called autonomous agents.

The first fundamental aspect is the generation and three-dimensional representation of these resources within the simulation scenario. The data relating to the construction site resources are not always available in the form of geometric data that allow the three-dimensional representation in the 3D virtual environment. The topic of BIM modeling of a construction site has already been widely discussed in research in recent years. In fact, analyzing the methods studied for the creation of a 4D BIM model of the construction site, it is common to all the modeling of the entities previously defined as static equipment, e.g. fences, gates, storage and storage spaces, construction site plants. As for the construction site resources, previously defined dynamic elements, there are two main lines of thought. On the one hand, for example, the studies that aim at optimizing in terms of organization of site spaces, worker safety through also VR training environment (Getuli et al., 2020) and verification of standards and rules of site design, consider necessary the parametric modeling of these elements and their inclusion within the 3D BIM model for the subsequent connection to the work activity for the creation of the 4D BIM model. Another line of thought is that these resources can be directly inserted as simple information related to the schedule activity and managed through the 4DBIM model, not necessarily as three-dimensional objects. As for human resources, such as workers, they are generally not implemented as three-dimensional objects or within the 4DBIM model but are managed through properties linked to the task schedule. In our case the process is based entirely on both the data of the resources related to the activity and their availability in the form of 3DObject.

Given the possible absence of these three-dimensional elements in the BIM models received and given the need to implement additional properties, within the game engine, for the use of these resources as an agent, it is essential to create a library of Site Agents, to be recalled during the simulation phase, through the identification code of the activity (TaskID). For the development of the geometric content of the objects of the new Agent library it is possible to exploit a classic library of BIM parametric families of the construction site through the same procedure shown in 3.3.1 for the creation of the simulation environment. For this reason, a modeling and organization strategy of the agent library has been defined to optimize the models (lower computational cost for BIM and Agent-Based models), maximizing the processing time of the same. Before proceeding with the modeling of these elements it was important to define the level of detail of the objects, depending on the results to be achieved. In this contribution, the need to simulate the volume of the macro-components of a machine, or the volume of the worker in an upright position, a level of simplified graphic representation may be sufficient. As far as construction machinery is concerned, a representation of elementary three-dimensional solids corresponding to the volumes of the dimensions of the relative machine components and of the spaces of interest is sufficient. Taking advantage of the considerations made in the studies on the theme of construction activity workplaces (Getuli et al., 2020), each BIM object will be composed of nested families, organized within the same category, containing the following two shared families corresponding to two types of spaces representative of the machinery: 1) Object Space: consisting of solids corresponding to the overall spaces of the components;

2) Hazard Space: consisting of volumes corresponding to the possible movement spaces of the vehicle and its components. For human resources, the same principle of simplified representation in spaces is adopted through the modeling of a single Object Space family represented by an elementary volume corresponding with cylinder, sized according to the average measurements of the human body. Each Object must be equipped with the same information content identified for the static entities and compiled with linking values related to the site planning (Fig.2), to be recallable and manageable even in the gaming environment.

Once the objects and their information content have been imported into Unity3D through the same procedure shown for the simulation environment, the 3DObjects require the implementation of additional properties to the graphic and informative ones, necessary to make them the "agents" of the system. Through the implementation of specific components, associated with the different volumes that make up the 3dObject, it is possible to exploit the functions of the Unity physics engine. In particular, the path was chosen to equip all 3dObjects with the Rigidbody component to activate them from the physical point of view and make them able to respond to the application of forces, and the Collider component to activate solid body behavior, managing and detecting collisions. An additional add-on, called NavMeshAgent, is required within each top-level nested family to help the agent understand which navigable surfaces of the model are, that is, the NavMeshSurface, defined for the static entities of the simulation environment model, on which to calculate its navigation path. These components and their parameters will be used by scripts through which it is possible to manage events and program response actions, creating interaction behaviors between agents and towards the environment, as described in the next paragraph.

3.2.3 Simulation rules for the navigation of construction site autonomous agents

The third aspect of the process requires the study and implementation of a Behavioral Engine, corresponding to the artificial intelligence that will govern the agents, composed of navigation rules and detection rules, which can be implemented within the Unity system through different scripts. In artificial intelligence, an autonomous agent is an intelligent agent (IA) which perceives its environment, takes actions autonomously in order to achieve goals. The core of this approach is the autonomy of the agent, provided with a set of behavioural rules able to interrogate the surrounding environment or his internal state, make decisions and performs actions that change its status as well as the built environment in a continuous perception-decision-action cycle. In this approach, the built environment is mainly passive and the use phenomenon emerges from the combination, iteration and interference of the behaviours of the n agents (Simeone et al., 2017).

In order to simplify the problem of management and control of the agent or NPC, the hierarchical Decision Making architectures of an agent, within the gaming environment, can be broken down into the following three sub-aspects: 1) Animation, is at the lowest level, depends on the other aspects and concerns the movements of the agent or its components (for example for human agents the movements of the limbs during movement or for machines the movement of a component for carrying out the processing). In this research, since the goal is not the visualization of the simulation but the recording and visualization of the collision points, it was decided to neglect this aspect, while approximating the animations of the movements of the equipment through the representation of the maneuvering spaces that assume the function of danger spaces. 2) Navigation is at the intermediate level of the structure and concerns the ways of searching for the route and navigating to a goal by the agent, avoiding obstacles. In Unity we have chosen to solve this using the system with navigation meshes. 3) At the highest level of the structure, we find the Behaviour, deciding the motivation and the goal to achieve. It is the part responsible of action selection, includes the mechanisms effectively selecting the actions to be carried out, according to the perceptions of the environment and internal state of an agent (Fig.4).

There are different approaches to obtain specific Agent AI behaviour and they are generally classified into deliberative and reactive.

- Reactive agents are elementary (and often memoryless) agents with a defined position in the environment. Reactive agents perform their actions because of the perception of stimuli coming either from other agents or from the environment; generally, the behavioural specification of this kind of agent is a set of condition-action rules, with the addition of a selection strategy for choosing an action to be carried out whenever more rules could be activated. In this case, the motivation for an action derives from a triggering event detected in the environment; these agents cannot be pro-active.
- Deliberative or cognitive agents, instead, are characterized by a more complex action selection mechanism, and their behaviour is based on so called mental states, on facts representing agent knowledge about the environment and for every possible sequence of perceptions, try to select a sequence

of actions allowing them to achieve a given goal. The internal state of agents is composed of three "data structures" concerning agent beliefs, desires, and intentions (BDI) (Fig.4). Beliefs represent agent information about their surrounding world; desires are the agent goals, while intentions represent the desires an agent has effectively selected, that it must some extend committed himself.

Both approaches can be useful for modeling the behavior of an intelligent entity (such as human resources and machinery) in a social context, such as the construction site. The choice must be related to the complexity and type of behaviors we want to achieve. Reactive approaches such as, for example, the Finite State Machine (FSM), are widely used in the gaming environment, in the representation of simple behaviors of enemy NPCs, in which the various actions are configured as variations of states in response to trigger events caused by the game user. This architecture focused on fast reactions/response to change in the environment and is focused on a set of pre-studied behaviors. This is difficult to implement and manage complex behaviors, as you must think and convert into code, all the possible states and transitions that an agent could have. An approach deliberative focused on long-term planning of actions, can handle more complex behaviors centred of basic goal as in the case del Goal Oriented Planning or the usefulness of an action as in the case of Utility System. With this approach the plan to carry out the action is not predetermined but will result from a decision-making mechanism of the best plan, to achieve a goal based on specific preconditions and effects in the case of the GOAP or the best course of action based on a score in the case of the Utility System. Looking at the example of behavior of the agents to be simulated, the development of an action planning system in relation to utility parameters seems the most correct approach (Fig.4).

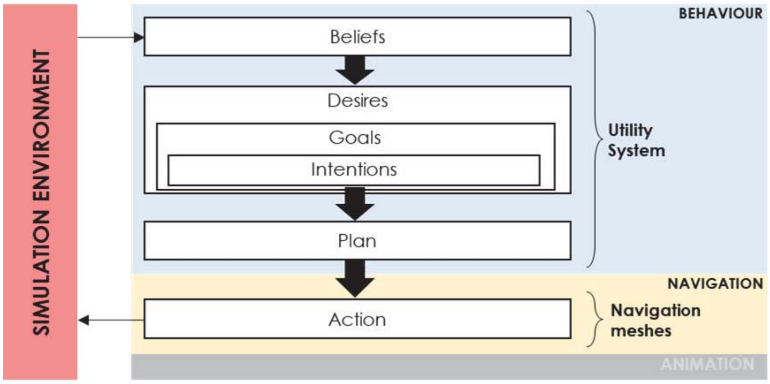

Fig. 4: Decision-making architecture of autonomous agent for Agent-Based Simulation of construction activities

For example, our human agent consists, on one hand of a series of internal state (e.g. energy, hunger, need service, etc.) to which numerical values, that vary over time according to specific functions, and the relatives limit values are assigned, on the other hand of a set of individual actions in terms of movement inside the construction site (e.g. work, rest, eat, use services). Considering a series of decision-making factors dependent on actions and the environment (action prize, action cost, target distance, time of day, etc.) and by linking scores to these that affect the internal state of the agent, the determination of the action to be achieved does not depend on the concatenation of the executable actions, but on the usefulness of such actions in terms of achieving the best score for the internal states value. The utility system calculates, according to the Principle of Maximum Expected Utility (MEU) (Russel & Peter, 2010) what is the most useful action to take at that moment by pushing the agent in carrying out one action rather than another. Our Utility System, with each simulation frames update, wonders what the most useful action to be performed to comply with the limit values of internal state considering the relative decrement functions and the score of decision-making factors. The same concept applies to equipment agents.

Collision detection method Survey rules mean all those criteria necessary for the detection and recording of data of interest to the simulation. With the aim of detecting the coordinates of the collision points that occurred during the simulation between worker agents and the hazard spaces of the equipment agents in addiction of the identification data of the agents, after the definition of the behavior properties of an agent, understood as conscious navigation of the virtual environment, it is necessary to generate properties that activate the agent to detect the collisions seen above. There are several methods of collision detection in Unity, in this case, the previous setting of the colliders of the agents allows the exploitation of the Contact point function through which the collision of the Object collider can be responded, requesting the name of the colliders that came into contact, the normal to the point of contact and possibly the printing of the contact point on a plane present in the simulation environment.

3.3 RECORDING AND PROCESSING OF SIMULATION DATA

The last aspects to be managed of the process concern the simulation settings. First, since the concept of probability of occurrence of a hazardous event is closely linked to its exposure time, the actual duration of the activity in question was chosen as the duration of the simulation. You must implement a script that uses Task ID code to implement the time schedule text file from which determine the duration of each specific task to be simulated. The possible availability of data relating to the sequence and duration of each individual entity present in the activity, is useful to insert in the simulation, the appearance/disappearance of the entities under construction and related equipment according to the real assembly sequence. Therefore, the simulation allows the autonomous navigation of the environment by the agents, the variation of the environment based on the appearance of the entities under construction, and the detection of the position and type of collisions that occur during navigation. The representation of such data in the form of heat maps, acts as an important support to the safety design decision-making process, carried out by the safety manager. The visualization of the distribution of the concentration of hazardous events on the map of the site layout is functional to the identification of the critical issues of the construction site for the definition of corrective safety measures in terms of organization and design of the construction site and planning of activities. The process involves the verification by simulation, even of the updated project models, up to the resolution of all the critical issues.

4. CONCLUSIONS

The current research on improving the safety of workers on site focuses on the study of different approaches aimed at optimizing site planning, mainly in terms of space management and activity planning. Several studies introduce technological innovation elements, demonstrating the usefulness of new tools such as VR, to increase the level of information and knowledge of the worker, through virtual training prior to the work activity; or monitoring and advanced detection tools to verify in real time the safety conditions in which workers are acting. In any case, the assessment of hazardous situations and related risks remains entirely in the hands of the safety manager, who provides subjective values in relation to his experience, on which organizational choices and prevention and protection measures that affect the success of the project depend.

The proposed system, therefore, thank to the evidence of the results of the agent-based simulation, aims to predict the outcomes of a work activity from the point of view of the probability of occurrence of collisions between workers and moving machinery within the construction site environment. This possibility provides the safety manager with an objective value on the probability of occurrence of such hazardous events through which he can make a more accurate estimate of the risk for the specific construction site, as well as to verify the results of the executive design choices, identifying any critical issues, allowing the implementation of corrective solutions that are actually feasible, already in the planning phase. In this work, an analysis was conducted using agent-based model and simulation approach, BIM Model, and Unity3D as a modeling and simulation engine. It has already been demonstrated that this approach is functional to the modeling of complex systems but general shortcomings for the development of 3D models have been found in the classic existing development platforms of Agent-Based models. Unity presents great potential and freedom for the implementation of the simulation scenario, for modeling the behavior of autonomous agents, providing the possibility to exploit existing project data from BIM models, as well as access to the existing official and third-party Unity library.

Regarding the future recommendations, the proposed frameworks it covers the probabilistic assessment of the occurrence of only hazardous events from contact between heavy vehicles and workers but could easily be extended to other hazardous situations such as, for example, falling from a height or falling materials from above. About the behavior of the simulation agents, the best artificial intelligence approach for the implementation of the decision-making mechanism that allows to identify the best action to be carried out in terms of navigation in the virtual environment of a construction site has been evaluated in this framework. The next step will be to identify a case study for implement and test the proposed Utility System, which will involve: 1) the study of the internal states that best represent the different types of agents, understood as dynamic entities of the construction site, and the related functions of decrease; 2) the definition of all the possible actions that they can be carried out by the agents, in terms of navigation the construction site during the work; 3) The identification of the decision-making factors which can really influence the desire of the worker to perform one action rather than another, calibrating the relative scores to obtain the most realistic behavior possible, in terms of navigation in the construction site area. Moreover, given the results that arise from the simulation, the correlation of the probability of occurrence of the hazardous event to an estimate of the risk, appears as the natural continuation of the research.

REFERENCES

Bina, K., & Moghadas, N. (2020). BIM-ABM simulation for emergency evacuation from conference hall, considering gender segregation and architectural design. *Https://Doi.Org/10.1080/17452007.2020.1761282*, *17*(5–6), 361–375. https://doi.org/10.1080/17452007.2020.1761282

Binhomaid, O. S. (2019). Construction Site-Layout Optimization Considering Workers ' Behaviors Around Site Obstacles , Using Agent-Based Simulation. *University of Waterloo*, 129.

Chavada, R., Dawood, N., & Kassem, M. (2012). Construction workspace management: The development and application of a novel nD planning approach and tool. *Electronic Journal of Information Technology in Construction*, *17*, 213–236.

Getuli, V., Capone, P., Bruttini, A., & Isaac, S. (2020). BIM-based immersive Virtual Reality for construction workspace planning: A safety-oriented approach. *Automation in Construction*, *114*(November 2019), 103160. https://doi.org/10.1016/j.autcon.2020.103160

Getuli, V., Capone, P., Bruttini, A., & Sorbi, T. (2022). A smart objects library for BIM-based construction site and emergency management to support mobile VR safety training experiences. *Construction Innovation*, *22*(3), 504–530. https://doi.org/10.1108/CI-04-2021-0062

Getuli, V., Giusti, T., Capone, P., Sorbi, T., & Bruttini, A. (2018). A Project Framework to Introduce Virtual Reality in Construction Health and Safety. *AlmaDL Journals, In_bo, New Frontiers of Construction Management Workshop*, *09*(13), 166–175. https://in_bo.unibo.it/article/view/8830/8950

Getuli, V., Ventura, S. M., Capone, P., & Ciribini, A. L. C. (2017). BIM-based Code Checking for Construction Health and Safety. *Procedia Engineering*, *196*(June), 454–461. https://doi.org/10.1016/j.proeng.2017.07.224

Goh, Y. M., & Askar Ali, M. J. (2016). A hybrid simulation approach for integrating safety behavior into construction planning: An earthmoving case study. *Accident Analysis and Prevention*, *93*, 310–318. https://doi.org/10.1016/j.aap.2015.09.015

Jin, Z., Gambatese, J., Liu, D., & Dharmapalan, V. (2019). Using 4D BIM to assess construction risks during the design phase. *Engineering, Construction and Architectural Management*, *26*(11), 2637–2654. https://doi.org/10.1108/ECAM-09-2018-0379

MacAl, C. M., & North, M. J. (2010). Tutorial on agent-based modelling and simulation. *Journal of Simulation*, *4*(3), 151–162. https://doi.org/10.1057/jos.2010.3

Marks, E. D., & Teizer, J. (2013). Method for testing proximity detection and alert technology for safe construction equipment operation. *Https://Doi.Org/10.1080/01446193.2013.783705*, *31*(6), 636–646. https://doi.org/10.1080/01446193.2013.783705

Marzouk, M., & Ali, H. (2013). Modeling safety considerations and space limitations in piling operations using agent based simulation. *Expert Systems with Applications*, *40*(12), 4848–4857. https://doi.org/10.1016/j.eswa.2013.02.021

Marzouk, M., & Daour, I. Al. (2018). Planning labor evacuation for construction sites using BIM and agent-based simulation. *Safety Science*, *109*(April), 174–185. https://doi.org/10.1016/j.ssci.2018.04.023

Mihić, M., Cerić, A., & Završki, I. (2018). Developing construction Hazard database for automated hazard identification process. *Tehnicki Vjesnik*, *25*(6), 1761–1769. https://doi.org/10.17559/TV-20180417105624

Moon, H., Dawood, N., & Kang, L. (2014). Development of workspace conflict visualization system using 4D object of work schedule. *Advanced Engineering Informatics*, *28*(1), 50–65. https://doi.org/10.1016/J.AEI.2013.12.001

Moon, H., Kim, H., Kim, C., & Kang, L. (2014). Development of a schedule-workspace interference management system simultaneously considering the overlap level of parallel schedules and workspaces. *Automation in Construction*, *39*, 93–105. https://doi.org/10.1016/J.AUTCON.2013.06.001

Pour Rahimian, F., Seyedzadeh, S., Oliver, S., Rodriguez, S., & Dawood, N. (2020). On-demand monitoring of construction projects through a game-like hybrid application of BIM and machine learning. *Automation in Construction*, *110*, 103012. https://doi.org/10.1016/j.autcon.2019.103012

Russel, S., & Peter, N. (2010). *Artificial Intelligence A Modern Approach* (Third Edit). Prentice Hall. https://zoo.cs.yale.edu/classes/cs470/materials/aima2010.pdf

Schwabe, K., Liedtke, S., König, M., & Teizer, J. (2016). BIM-based Construction Site Layout Planning and Scheduling. *16th International Conference on Computing in Civil and Building Engineering*, 679–686. http://www.see.eng.osaka-u.ac.jp/seeit/icccbe2016/Proceedings/Full_Papers/086-352.pdf

Schwabe, K., Teizer, J., & König, M. (2019). Applying rule-based model-checking to construction site layout planning tasks. *Automation in Construction*, *97*(October 2018), 205–219. https://doi.org/10.1016/j.autcon.2018.10.012

Simeone, D., Cursi, S., & Coraglia, U. M. (2017). Modelling Buildings and their Use as Systems of Agents. *Proceedings of the International Conference on Education and Research in Computer Aided Architectural Design in Europe*, *1*, 85–92. https://doi.org/10.52842/conf.ecaade.2017.1.085

Stieler, D., Schwinn, T., Leder, S., Maierhofer, M., Kannenberg, F., & Menges, A. (2022). Agent-based modeling and simulation in architecture. *Automation in Construction*, *141*(June), 104426. https://doi.org/10.1016/j.autcon.2022.104426

Tak, A. N., Taghaddos, H., Mousaei, A., Bolourani, A., & Hermann, U. (2021). BIM-based 4D mobile crane simulation and onsite operation management. *Automation in Construction*, *128*, 103766. https://doi.org/10.1016/j.autcon.2021.103766

Teizer, J., & Cheng, T. (2015). Proximity hazard indicator for workers-on-foot near miss interactions with construction equipment and geo-referenced hazard areas. *Automation in Construction*, *60*, 58–73. https://doi.org/10.1016/J.AUTCON.2015.09.003

Vahdatikhaki, F., & Hammad, A. (2015). Risk-based look-ahead workspace generation for earthwork equipment using near real-time simulation. *Automation in Construction*, *58*, 207–220. https://doi.org/10.1016/J.AUTCON.2015.07.019

Younes, A., & Marzouk, M. (2018). Tower cranes layout planning using agent-based simulation considering activity conflicts. *Automation in Construction*, *93*(May), 348–360. https://doi.org/10.1016/j.autcon.2018.05.030

Zhang, S., Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C. M., & Teizer, J. (2015). BIM-based fall hazard identification and prevention in construction safety planning. *Safety Science*, *72*, 31–45. https://doi.org/10.1016/J.SSCI.2014.08.001

Zhou, Y., Ding, L. Y., & Chen, L. J. (2013). Application of 4D visualization technology for safety management in metro construction. *Automation in Construction*, *34*, 25–36. https://doi.org/10.1016/j.autcon.2012.10.011

Zou, Y., Kiviniemi, A., & Jones, S. W. (2016). Developing a tailored RBS linking to BIM for risk management of bridge projects. *Engineering, Construction and Architectural Management*, *23*(6), 727–750. https://doi.org/10.1108/ECAM-01-2016-0009