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AGENT-BASED SIMULATION FRAMEWORK FOR ENHANCED CONSTRUCTION SITE RISK ESTIMATION AND SAFETY MANAGEMENT

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SUMMARY: *Despite ongoing efforts to boost safety through new regulations and technologies, the construction industry still grapples with significant safety and accident issues. Construction sites are complex and dynamic environments, teeming with workers, vehicles, and machinery engaged in various activities. This complexity often leads to unpredictable hazardous events, making safety management a challenging task heavily reliant on the experience of safety managers. This paper introduces a framework to aid safety managers in risk assessment by developing an advanced simulation system. The system merges 4D Building Information Modeling (BIM) Simulation with 3D Agent-Based Modeling and Simulation (ABMS) within a game engine environment. This integration allows for the simulation of various entities (agents) and their interactions on a construction site, offering a detailed view of potential hazards. The proposed system features an automatic Prevention through Design (PtD) method. This method predicts hazards by analyzing the likelihood of occurrence, vulnerability, and exposure values during the planning phase. It simulates agent behaviors, records interactions leading to hazardous events, and visualizes these interactions as hazard exposure heatmaps in the 4D BIM model. The model reflects various site configurations over time, helping safety managers to strategically organize activities and workspaces to minimize risks. The framework follows the ISO 31000:2018 risk definition and addresses the complexity of construction site systems and their risk management issues. It discusses the key components of the framework, including the rules of agent behavior based on game theory, management of BIM data for 3D scenario creation, and a detection and visualization system for monitoring agent interactions. Overall, this framework seeks to enhance risk assessment effectiveness in the construction industry by leveraging BIM and advanced simulation techniques to provide valuable insights for improving site safety management.*

KEYWORDS: *Risk estimation, Hazard Exposure, Construction site planning, Agent-based Modeling and Simulation (ABMS), Building Information Modelling (BIM), BIM 4D, Health & Safety management, Artificial intelligence, Game Engine.*

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1. INTRODUCTION

The contemporary construction industry faces persistent challenges in ensuring safety and accident prevention, despite advancements in safety regulations and technology integration. The complex and dynamic nature of construction sites, involving multiple entities and spatial configurations, makes safety planning and risk estimation challenging within Health and Safety (HS) management.

Traditional risk assessment methods, relying heavily on human expertise, often struggle to address the intricacies of construction site dynamics. Manual methods may not accurately predict or prevent potential hazards, leaving sites vulnerable to accidents. Therefore, there is a pressing need for innovative approaches leveraging advanced technologies to enhance safety management.

This study proposes a comprehensive framework that revolutionizes safety management by integrating 4D Building Information Modeling (BIM) Simulation with 3D Agent-Based Simulation (ABMS) in a game engine environment to perform risk analysis. This fusion provides a multifaceted perspective on safety, enabling the prediction and visualization of hazardous events, as well as testing site layout design and activity planning. The framework aims to empower safety managers with a proactive approach to Predictive Safety through Design (PStD), enabling early identification and visualization of potential hazards during project planning. By combining these methods and technologies, the framework aims to enhances safety practices and fosters a safer working environment for construction personnel.

To contextualize the need for such innovation, this introduction outlines the complex nature of construction sites and the limitations of traditional risk assessment methods. It emphasizes the persistence of injuries in the industry and the shortcomings of subjective risk assessments. The subsequent sections will explore into the proposed framework in detail, highlighting its potential to reshape safety management practices and mitigate risks associated with construction activities.

While legislative frameworks and risk assessment methodologies provide essential tools for enhancing construction site safety, they are not without limitations. Errors in risk assessment can arise due to factors such as incomplete data, inadequate training of assessors, or oversights in the identification of hazards. Additionally, the dynamic and evolving nature of construction sites can introduce uncertainties that traditional risk assessment methods might struggle to capture accurately. Suboptimal risk assessment can lead to repercussions that extend beyond the safety of workers. Inaccurate risk evaluation can result in the misallocation of resources, project delays, increased costs, and even legal consequences. This interaction between risk assessment accuracy and the overall construction process underscores the need for innovative approaches, such as the integration of BIM 4D models and agent-based simulations, to enhance the precision and effectiveness of risk assessment practices.

This study on the integration of 4D Building Information Modeling (BIM) Simulation with 3D Agent-Based Simulation (ABMS) for safety management in construction sites is part of a broader research initiative focused on advancing risk estimation through advanced simulations. The first study (Sorbi et al., 2022) in this series introduced a general framework for risk assessment using advanced simulations of this nature. It laid the groundwork for understanding the potential of integrating BIM and ABMS in safety management practices within the construction industry.

Building on this foundation, this contribution is going to investigate deeper into the framework, offering more detailed insights into its structure, flow, and methods of implementation, proposing practical approaches for integrating BIM and ABMS within a cohesive system aimed at enhancing safety practices and reducing risks on construction sites. Moving forward, the study will continue with the analysis and evaluation of the proposed advanced simulation system through experiments on a model and test scenarios. This iterative process aims to refine and optimize the framework, ensuring its effectiveness in predicting, visualizing, and mitigating potential hazards in construction environments.

By contributing to the body of knowledge on the integration of BIM and ABMS for safety management, this research endeavours to provide valuable insights and practical solutions to improve safety practices and protect the well-being of construction personnel.

2. BACKGROUND

Over the past few years, the construction industry has witnessed a significant surge in the adoption of new tools and information technologies, particularly in the realm of safety management for workers on construction sites. Building Information Modeling (BIM), alongside new simulation methods and the utilization of game engines, has experienced notable growth in their application to safety management practices.

BIM has emerged as a transformative force in the construction industry, reshaping how projects are conceived, designed, executed, and maintained. Initially renowned for fostering collaboration and efficiency in design and construction processes, BIM's integration into safety management introduces a new era of proactive risk assessment and hazard mitigation. BIM's 3D visualization capabilities play a pivotal role in identifying risks associated with temporary facilities during safety planning stages (Kim et al., 2011). By integrating BIM, safety managers can detect spatial clashes and anticipate project dangers throughout the construction lifecycle (Alaloul et al., 2023). Building Information Modeling (BIM) and Virtual Reality (VR) can be simultaneously used to site design validation and related workers' training using that system (Getuli et al., 2018). Additionally, BIM facilitates systematic risk management in construction, serving as a foundational platform for further risk analysis using digital technologies (Zou et al., 2017).

Furthermore, the integration of 4D BIM, which links construction sequences to the 3D model, enhances safety assessment by providing insights into the temporal dimension of construction. This integration allows for the visualization of construction sequences, high-risk phases, and potential clashes between activities, resources, and workers. Safety managers can strategically plan safety interventions, allocate resources, and optimize work schedules to minimize safety risks during critical construction phases (Jin et al., 2019). A workspace conflict visualization system based on a virtual environment such as 3D and 4D objects enables the real time detection of workspaces' conflict. If project managers can check workspace conflict between activities by this system, they can reschedule the conflicted activities within float time to minimize the conflict and maximize the constructability for concurrent activities (Moon et al., 2014).

Recent advancements in computer simulations, supported by increased computing power, have led to the emergence of techniques that closely resemble actual systems, with agent-based modelling and simulation (ABMS) standing out as one of the most powerful simulation techniques (Sorbi et al., 2022). ABMS is a dynamic and adaptable methodology that models complex systems through individual agents' interactions and behaviors. It finds applications in various domains, including economics, social sciences, and ecology. In the construction industry, ABMS offers insights into decision-making, logistics, and resource allocation by modeling the distinct behaviors of different agents, such as construction workers, machines, or materials (Ahn & Lee, 2015).

The individual merits of BIM and ABMS have sparked significant interest among researchers, leading to increasing exploration of their integration to tackle highly complex challenges across various domains. This integration combines BIM's robust data visualization and management capabilities with ABMS's dynamic, behavior-driven modeling approach, providing innovative tools for simulating interactions, optimizing systems, and enhancing decision-making processes in environments characterized by high complexity and uncertainty. A hybrid framework has been proposed that combines ABMS with system dynamics to model unsafe worker behaviors and their impact on project performance, offering deeper insights into behavior-driven safety management (Nasirzadeh et al., 2018). Similarly, other studies emphasize the importance of modeling human factors and dynamic interactions in construction safety as emergent phenomena, addressing the critical role of agent-based approaches in managing complex safety challenges (Palaniappan et al., 2007).

In the context of emergency planning, BIM integrated with ABMS has been applied to optimize evacuation plans by simulating human behaviors under fire scenarios. This approach evaluates evacuation performance by considering factors such as building layouts and fire dynamics, enabling architects and safety planners to refine designs to better accommodate emergency situations (Sun & Turkan, 2019, 2020).

Dynamic layout optimization in construction also benefits from the integration of BIM and ABMS. Studies have demonstrated the potential of this combination to simulate human behavior and improve building design by modeling occupant actions under various scenarios (Cheng & Vincent J. L., 2013). Further contributions to this field include the development of hybrid hierarchical agent-based simulation frameworks to assess building layouts during post-earthquake evacuation scenarios. By integrating BIM data into ABMS, these frameworks simulate occupant behaviors during evacuations, offering critical insights for early-stage architectural and non-structural design decisions (Hassanpour et al., 2022). Additionally, BIM-based probabilistic non-structural damage assessments have been incorporated into agent-based post-earthquake evacuation simulations, improving analyses of how damage impacts evacuation processes. These studies underscore the importance of using detailed BIM data as the foundational input for ABMS simulations, enabling more effective behavior-driven analyses and safety strategies (Hassanpour et al., 2023).

Finally, reviews of ABMS applications in construction highlight its broad utility in addressing decision-making complexities and optimizing processes, emphasizing its cost-effectiveness in modeling interactions and enhancing project efficiency (Araya, 2020; Khodabandelu & Park, 2021) Collectively, these studies underline the versatility and transformative potential of integrating BIM's data-rich visualization with ABMS's dynamic simulations to enhance safety, optimize resource management, and create more resilient construction environments.

In conclusion, the integration of BIM and ABMS has demonstrated significant interest and satisfactory results across various domains where probabilistic assessments, preventive evaluations, and agent-based predictions are essential for understanding and addressing the complexity of systems and their surrounding environments, encompassing not only human agents but also other dynamic entities and environmental factors. This integration holds immense potential to enhance safety management practices, both in construction and in other fields, ushering in a new era of proactive hazard identification, intervention planning, and risk mitigation strategies.

3. RESEARCH CONTEXT AND OPEN ISSUE

Risk management in the realm of worker safety in construction refers to a systematic and proactive approach aimed at identifying, assessing, controlling, and mitigating potential hazards and dangers that can affect the health and well-being of construction workers on job sites. It involves a strategic framework that allows construction actors reduce the likelihood of accidents, injuries, and fatalities while also ensuring compliance with safety regulations. Considering the importance of risk management in ensuring the safety of construction workers, this research aims to research deeper into several key themes. In the subsequent sections, we will explore the risk management process tailored specifically for the safety of construction workers, examine pertinent health and safety legislation affecting the construction industry, and analyse what is hazards on construction sites. Through an exploration of these themes, this study endeavors to offer a thorough grasp of the complexities and nuances surrounding worker safety within the construction industry, thereby enriching the discourse, and framing of the ongoing challenges in risk management. With a specific focus on leveraging advanced BIM Agent-based simulation systems for risk estimation, our research aims to confront these challenges head-on, providing innovative solutions and insights to enhance safety protocols and practices in construction settings.

3.1 Risk management process for worker safety in construction

A systematic and proactive approach to risk management is paramount in the construction industry, where workers are exposed to a myriad of potential hazards and dangers on job sites. By implementing a strategic framework for risk management, construction stakeholders can effectively identify, assess, control, and mitigate these hazards, thereby safeguarding the health and well-being of workers. This approach not only reduces the likelihood of accidents, injuries, and fatalities but also ensures compliance with stringent safety regulations set forth by governing bodies.

Central to the risk management process is the comprehensive identification of potential hazards and dangers present in the construction environment. This involves a meticulous assessment of various factors such as work processes, equipment, materials, and environmental conditions that could pose risks to workers' safety. Through this rigorous hazard identification process, construction actors gain insights into the specific risks inherent in their operations, allowing them to devise targeted risk management strategies.

Once hazards are identified, the next step is to assess their potential impact on worker safety. Risk assessment involves evaluating the likelihood and severity of potential incidents resulting from these hazards. By quantifying the level of risk associated with each hazard, construction stakeholders can prioritize their efforts and allocate resources effectively to mitigate the most critical risks first.

Following risk assessment, control measures are implemented to minimize or eliminate identified hazards. These measures may include organizational processes, sequence scheduling and activities overlapping management, workspace and resource management, engineering controls, administrative controls, and the provision of personal protective equipment (PPE) to workers. By implementing a combination of preventive measures, construction stakeholders create a safer work environment and reduce the likelihood of accidents and injuries.

Continuous monitoring and review of safety measures are integral to the risk management process. Regular inspections, audits, and safety performance assessments allow construction actors to identify emerging hazards, evaluate the effectiveness of existing control measures, and make necessary adjustments to enhance safety protocols.

The on-site risk management process is made up of very important steps that affect the operational phase of the construction process, which would not be feasible without the analyses, evaluations and solutions defined by managers during the risk management steps necessarily in the planning phase. Lu et al., 2015 highlight that safety management in construction involves identifying hazards before they occur as a core process. Traditional safety checking is manual and time-consuming, and the integration of new technology is essential for efficiency.

The proposed study is specifically situated within the risk assessment step of the risk management process outlined by ISO 31000:2018. In this context, the emphasis lies on the risk analysis phase of construction site activities, one of the most critical aspects of Risk Management. By focusing on this phase, the study aims to provide a comprehensive understanding of the factors influencing the likelihood of hazardous events (H) and their consequences.

Through the integration of advanced methodologies, including BIM (Building Information Modeling) and Agent-Based Simulation, the study seeks to enhance the accuracy and efficiency of risk assessment processes. By leveraging these innovative approaches, construction stakeholders can gain valuable insights into the dynamic nature of hazards and make informed decisions to mitigate risks effectively. Ultimately, the goal is to contribute to the development of proactive risk management strategies that prioritize worker safety and promote a culture of safety excellence within the construction industry.

3.2 Health and safety statistics in construction environment

Accident statistics in the construction industry paint a stark picture of the challenges faced by workers in this field. Despite ongoing efforts to improve safety, construction remains one of the most hazardous professions, with construction workers facing a higher risk of accidents and injuries compared to many other industries. These incidents encompass a wide range of scenarios, including falls, falling object, equipment-related accidents, machine-related accidents, electrical mishaps, and more.

The significance of these statistics cannot be overstated, as they highlight the pressing need for continued safety initiatives, stringent regulations, and ongoing training to safeguard the well-being of construction workers and reduce the human and financial costs associated with workplace accidents.

Accurate accident statistics play a vital role in shaping safety policies and practices within the construction industry, both at the national and international levels. Organizations such as the International Labour Organization (ILO), the International Social Security Association (ISSA), and the International Organization for Standardization (ISO) play key roles in collecting and disseminating global accident data and state that the construction industry is the sector with the highest number of fatal accidents each year, with numbers always growing. In addition, highlight that construction consistently ranks among the highest-risk industries, with a substantial number of non-fatal injuries and illnesses reported each year.

These statistics underscore the urgent need for standardized safety protocols, increased awareness, and collaborative efforts on a global scale to mitigate the risks faced by construction workers and improve overall safety in the industry.

3.3 Health and safety legislation

Health and safety legislation in construction sites is indeed governed by national and regional laws and regulations, which establish legal obligations for various stakeholders involved in construction projects. These regulations typically require employers, employees, contractors, and other parties to conduct thorough risk assessments before initiating construction work. During the preconstruction phase, this involves identifying potential hazards, assessing risks, and implementing measures to mitigate or eliminate them.

In the United States, the Occupational Safety and Health Administration (OSHA) plays a central role in regulating occupational health and safety standards for construction sites. OSHA sets and enforces safety standards to protect construction workers and ensure safe working conditions.

In Europe, health and safety regulations for construction sites are governed by a combination of national laws and directives issued by the European Union. The EU directives aim to harmonize safety standards across member states, ensuring a consistent level of protection for workers throughout the European Union.

In health and safety law, risk (R) is conceptualized as the product of likelihood (H) and vulnerability (V) of a hazardous event causing harm or injury due to exposure (E) to workplace hazards (ISO 31000:2018 - Risk Management - Guidelines). Hazards in construction sites can encompass various factors, including physical, chemical, biological, ergonomic, and psychosocial elements. The concept of risk acknowledges that workplaces inherently pose potential dangers that must be identified and managed to protect workers' health and safety.

Despite the fundamental importance of risk evaluation, it remains challenging for management systems due to the complexity of construction activities, overlapping tasks, and the diverse range of resources involved. This complexity makes predicting and managing risks in construction environments difficult, highlighting the need for robust risk assessment methodologies and management strategies.

3.4 Construction site hazard

The concept of hazard within the construction industry is multifaceted and requires careful consideration, especially when developing frameworks for BIM simulation and agent-based estimation of the likelihood of hazardous events. Hazards are defined as intrinsic properties or characteristics with the potential to cause harm to people, property, or the environment (D.Lgs. 81/08). Starting from the definition, we can be said that a hazard is the potential ability to cause harm to people (hazardous event) and it is useless to provide an estimate, unlike risk which instead expresses the probability that an event capable of causing damage in that specific context will occur. In the concept of hazard there is therefore the objectivity of the physical presence of the potential source of damage to health and safety, be it a machine, a substance, a process, a system, so hazards can be a risk source; the risk, on the contrary, is not a physical entity and is not linked so much to an object, a machine or a plant, but to the materialization of a situation that makes the occurrence of the harmful event capable.

Understanding when hazards transition into risks is challenging but crucial for safety management. It involves identifying hazardous situations and implementing safety measures, particularly during the planning phase of construction projects. The proposed system aims to support safety managers during risk analysis, to assess the likelihood of this transition from hazard to risk occurring to evaluate associated risks level and implementing preventive measures for the treatment of this risk.

Various hazard classification systems have been proposed, typically based on frequency, severity, and risk levels. Zhang's classification system is particularly relevant, categorizing hazards into unsafe work conditions, activity-based hazards, and activity-interaction hazards. These classifications aid in identifying and representing hazards and risks within BIM and agent-based simulations of construction site activities.

Formal and explicit representation systems for building products, work activities, and safety management aspects are essential for integrating safety and hazard into BIM and simulation scenarios. Zhang et al., 2015 provides a structured framework ontology for formalizing safety management knowledge, organizing it into domains such as the construction product model, construction process model, and construction safety model. This ontology links construction elements, processes, resources, and hazards, facilitating hazard identification in relation to the project schedule.

Occupational health and safety organizations recommend performing job hazard analyses (JHA) to identify hazards faced by construction workers and assess associated risks. Among these and considering the definition of risk R=H*V*E (par. 3.3), this paper presents the framework for the implementation of an advanced BIM and Agent-based simulation system of construction site activities for risk analysis to support safety manager during risk management activity.

4. RESEARCH FRAMEWORK AND METHODOLOGY

Agent-based modelling and simulation is an approach to model complex systems to understand the emergence of these events. The Aim of the present contribution is to build a novel framework for the introduction of an Agent-Based Model Simulation analysis approach to estimate risk variables, particularly the likelihood of occurrence of hazardous event (H) to support safety manager during risk assessment and project and safety planning activity.

As shown in Figure 1, in this research, three modules are outlined, each contributing distinct facets to the advancement of construction site safety through advanced simulation technology. Within these modules, the phases of the risk assessment process according to ISO 31000:2018 are articulated, where, starting from the BIM programming of the intervention, the BIM and agent-based simulation system supports the risk analysis phase by providing useful information for the subsequent phases of risk assessment and treatment. These modules collectively form a comprehensive framework aimed at enhancing risk management practices within the construction sector. Through integration of 4D BIM design, site data, and Agent-Based models, this framework offer innovative solutions for evaluating and mitigating potential hazards, as described in more detail below:

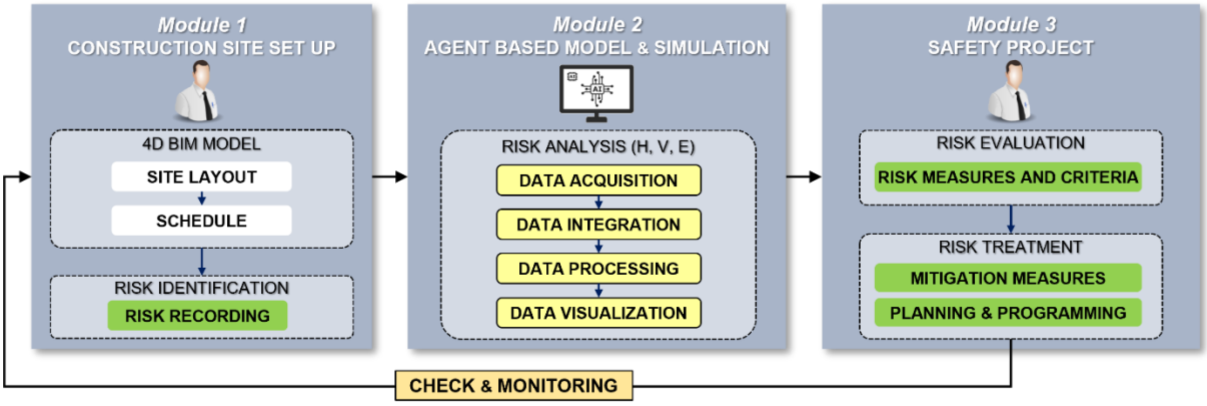

Figure1: Framework of BIM and Agent-Based Simulation for Risk Assessment of Site Activities. The framework is divided into three main modules: Construction Site Set Up, Agent-Based Simulation, and Safety Project, supported by a continuous Check & Monitoring process to enhance risk management and decision-making.

- **Module 1**: This module marks the initial phase of the framework, wherein the safety manager formulates an initial hypothesis for planning the site layout and schedules activities accordingly. These plans are then translated into a 4D Building Information Modeling (BIM) model of the project and construction site, aligning with the predetermined timeline of activities. Following this, the focus shifts towards identifying risks (ISO) stemming from the planning and programming decisions made. In this module we emphasize the integration of the virtual simulation environment within a game engine, leveraging 4D BIM design and site data. Subsequently, these resources are utilized for risk analysis through BIM Agent-based simulation of activities. These datasets facilitate the creation of a 3D virtual scenario corresponding to a specific moment in time (activity n) and the configuration of the construction site. Schedule data aids in identifying planning specifics for each activity, establishing links to relevant BIM objects. Furthermore, data regarding the type and quantity of site entities, such as human resources, vehicles, and machinery, are integrated to load corresponding 3D objects into the simulation (Sorbi et al., 2022).
- **Module 2**: Once the potential risks associated with site organization and activities are identified, in accordance with ISO standards, the risk analysis phase ensues, during which expert technicians estimate values for the variables upon which risk depends (H, V, E). Despite their experience and the current techniques and data used for estimating these variables, the complexity of simultaneous activities and resources makes it challenging to anticipate all potential hazardous situations that may arise during construction. At this point, the BIM Agent-based simulation system for risk estimation comes into play by supporting the safety manager in the estimation on the likelihood of occurrence of hazardous events (H), and to obtain information about Vulnerability (V) and Exposure (E) of those events. This module encompasses all stages of Agent-Based model simulation for site activities development within the game engine environment, integrating a three-dimensional virtual

representation of the site and design project. While geometric entities and their associated data provide a foundation, additional properties derived from studies on variables, rules, risks, and hazard events are essential for advanced simulation of site dynamics and risk analysis. Schedule data guides agent implementation and simulation progression, enabling agent-based simulation for each planned site activity. Specially developed algorithms facilitate the detection and representation of hazardous events within the virtual environment.

- **Module 3**: Following the analysis, the Safety Manager conducts a risk evaluation to determine the acceptability level and prioritize interventions accordingly. Subsequently, the risk treatment phase ensues, wherein multiple solutions may be employed, including alterations to the site project, work schedule adjustments, and the utilization of technical specifications and resources. Utilizing data obtained from the risk analysis via BIM Agent-based simulation of activities, the Safety Manager gains objective insights into hazards and their likelihood of occurrence within the scheduled work activities. The proposed system not only aids technicians in risk estimation but also empowers safety managers and project leaders to automatically conduct simulations during the planning phase. This enables the assessment of safety implications associated with various planning decisions concerning worker safety and project objectives.

As already mentioned in par.1 This study is part of a broader research effort aimed at creating an advanced simulation system combining BIM and Agent-Based Simulation for risk assessment. The system serves as a support tool for safety managers during site planning, striving to achieve an optimal balance between project objectives and worker safety. Subsequent sections will examine into the methodologies for developing the first two modules, which form the core of the study and enable BIM-Agent-Based simulation of site activities to generate hazard exposure likelihood heatmaps. Figure 2 provides an overview of the study's methodology, from conceptualization to prototype implementation.

5. TOP LEVEL ARCHITECTURE

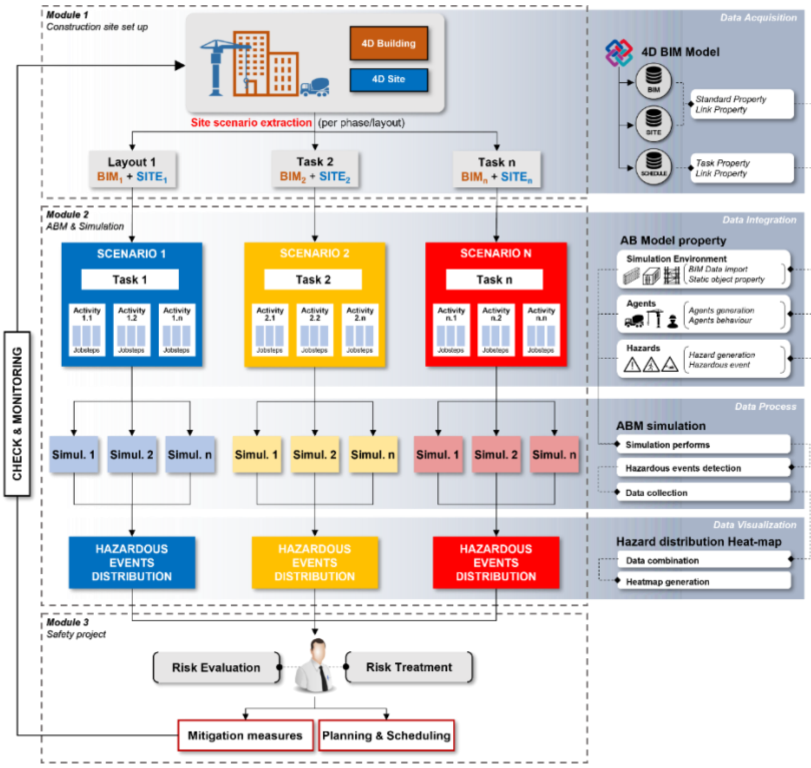

Figure 2: BIM and Agent-Based Simulation System Architecture. This figure expands the previous framework, detailing each module's layers: Data Acquisition (importing site data), Data Integration (linking and structuring information), Data Process (simulating hazards and events), and Data Visualization (heatmap generation and analysis).

The top-level architecture of the proposed methodology is shown in Figure 2, illustrating the functioning, relationships, and dependencies between BIM-based 4D design and planning activities and the BIM and Agent-based simulation system for construction site activities. The architecture highlights the potential benefits of visualizing predictive heatmaps of hazardous event occurrences on the BIM model.

Following the initial overview of the system framework provided above, subsequent sections will focus into each aspect of its architecture. Each workflow module will be explored in detail, outlining the contents of various steps within the process layers. These steps are identified for the implementation of the advanced BIM and ABS system for construction site activities aimed at risk assessment.

5.1 Module 1: 4D BIM model

Module 1 comprises a single *Data Acquisition Layer*, serving as the initial phase of the information flow from the BIM model. This layer is essential not only for project and construction management processes but also for triggering safety management activities, because the data that are implemented in the various steps of development of the 4D model are exploited in the most diverse ways, in this case for evaluations related to the safety of work activities. At this stage, we are in the 4D planning process, where we have an integrated 3D BIM model organized according to the construction schedule. The BIM model and its components are broken down into temporal activities, each associated with the relevant site resources. The necessary data (Figure 3), organized according to IFC open format standards, are retrieved from the 4D BIM models of the project and the construction site. These data are stored in a shared database in a format readable by the simulation system, based on their function.

5.1.1 Data acquisition Layer

This phase involves analysing the characteristics and identifying the properties required for the 4D BIM model to be compatible with acquisition and processing by the BIM Agent-Based Simulation System. As outlined by Sorbi et al., 2022, beyond the standard properties such as geometric data, coordinates, and identification data, additional parameters are necessary to address simulation-related aspects, that need to be implemented during the processing of the 4D BIM model. This includes generating a federated coordination model organized by phases, incorporating models from all disciplines, including the construction site model containing provisional elements such as zones, spaces, equipment, site facilities, and infrastructures, the execution of the various components of the project model.

Advanced project management software with integrated 4D BIM modeling capabilities allow for the export of project and 4D programming data in IFC format. Each entity, whether modelled or not, along with its information content, is organized under relevant tasks, activities, and job steps of the project's work scheduling.

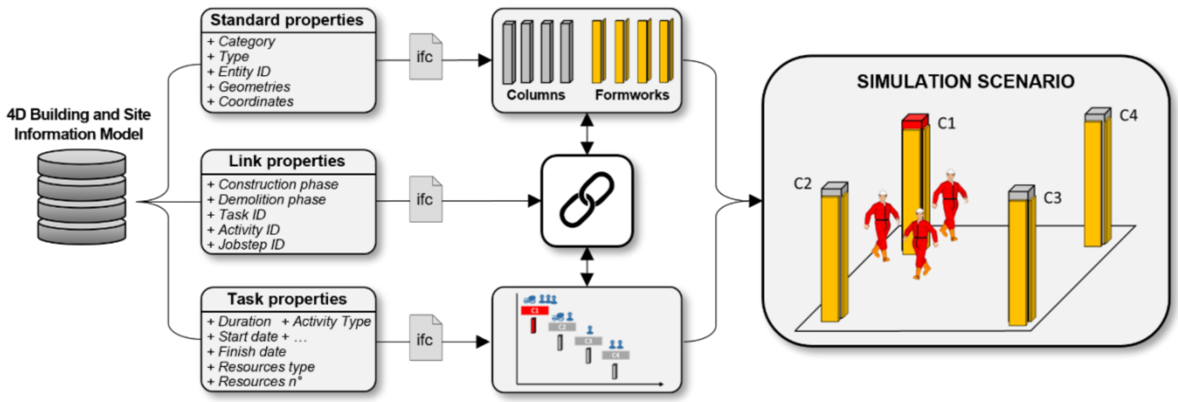

Figure 3: 4D BIM Data for Simulation Scenario Generation. The figure shows how Standard Properties, Link Properties, and Task Properties are used to create scenarios for agent-based simulations.

This organization aligns with the logic of 4D BIM modeling and serves both the creation of three-dimensional simulation scenarios and the connection of data to the scene and simulation management (Figure 2). This organization is repurposed by implementing and leveraging the following data (Figure 3):

Standard properties: To kickstart the implementation phase, we seamlessly integrate properties like Category, Types, and Identification data into our 3D BIM model in accordance with the IFC classification structure. This data will facilitate the structured decomposition of the project thanks to clear definition BIM model's entities of work activities.

Link properties: In line with the composition scheme outlined in Figure 3, each component must be classified with parameters that allow the connection between the data of the 3D model and the information relating to the site activities as per the program. Property indicating the Creation/Demolition phase to contextualize it within the correct site configuration and as a filtering system the appropriate simulation scenario context. Additionally, further such as Task ID, Activity ID, and Jobsteps ID, normally used for to expand the level of detail of the programming, allow to manage various site and project components within each simulation scenario and connect them to relevant task properties, both in the 4d BIM model and in the simulation.

Task properties: As mentioned above, the identification and link parameters provide the means for transferring the timing information to the simulation. Data that allows the management of the project and site model entities in the simulation environment as well as the generation of the resources expected for the execution of the activity.

By leveraging the principles and logic underlying the creation of a 4D BIM model, the basic 3D scenario and dataset required for the performance of BIM Agent-Based simulation of planned site activities for risk assessment can be established.

5.2 Module 2: BIM agent based simulation

Agent-based modeling and simulation (ABMS) is a novel approach to modeling systems consisting of autonomous, interacting agents (MacAl & North, 2010). This methodology is particularly useful for modeling the dynamics of complex systems and complex adaptive systems, where emergent order often arises from the interactions of these agents. ABMS involves modeling behaviors, whether human or otherwise, and is employed to observe the collective effects and emergent phenomena resulting from these interactions (Khodabandelu & Park, 2021). Given the dynamic and complex nature of construction problems, characterized by numerous and volatile factors, ABMS offers an effective approach to investigating various construction issues, predicting outcomes, and ultimately selecting optimal solutions.

In this study, we propose a simulation model based on BIM and Agents for simulating construction site activities and recording and visualizing data on hazardous events that emerge from agent's interactions. The goal is to provide safety managers with a new tool to detect agent's interactions information for the estimation of likelihood of hazardous events (H), and information about the agents that caused the interaction for estimating vulnerability (V) and exposure level (E).

This module, organized in three layers, forms the core of the proposed framework, and discusses the key aspects identified for implementing the advanced simulation system.

5.2.1 Data Integration layer

The system relies on the classification of site entities as proposed by Sorbi et al., 2022, which accounts for the complex and overlapping nature of construction activities. This classification into two macro-groups, static and dynamic entities, is necessary because each entity requiring distinct configuration within the simulation environment of the game engine based on their characteristics and role in the construction site system. We will start below by treating static entities as the starting point of the whole process.

Simulation Environment: The simulation environment consists of static entities, entities lacking intelligence that function as fixed or temporary equipment or obstacles within the construction space, playing passive roles in construction activities. Static entities, particularly the components of the project's BIM model, hold significant importance in the system. They encompass the use of other provisional static entities from the construction site's BIM model, along with 4D data related to their installation activity, termed as *Task Properties.* These entities encompass contextual elements, completed and under-construction structures, static equipment, etc. To generate the simulation virtual environment from IFC files, two crucial steps are proposed.

- **Import Data**: Sorbi et al., 2022 propose a practical method for transferring the geometric and informational content of static entities from the BIM model. This method involves preprocessing the IFC file using the IfcConverter utility of the open-source IFCOpenShell library. The geometry of the model entities is imported using the Obj format, while the data of each entity is imported using the

Xml format. This process optimizes geometry representation and rebuilds the data structure. By utilizing a unique entity reference parameter, such as the Entity ID as recommended, or the commonly used ifcGUID, to name components in Obj format and to group the data of each component in Xml format, one can leverage this value during simulation time as a means of connection and access key to the hierarchical structure of the component data. The availability of the component's geometry and its data structure enables its full exploitation within the game engine and, consequently, in the simulation.

- **Static Game Object Properties**: Each game object is categorized and equipped with properties that define its design and planning characteristics within the simulation environment. Game engines facilitate the activation of physical properties such as gravity, mass, and friction, allowing for realistic behavior simulation and agent responses. In this way, these entities can be exploited by agents, in relation to their function in reality and therefore in simulation. Therefore, considering the exploitation that the agent makes of the various static entities of the construction site, and considering the machines moved by a man who are also agents, the following two categories of entities have been proposed:

  1) Action Target, entities that represent the area or the reference point for carrying out actions related to site activities; 2) Navigation surfaces, highlighted in blue in fig, which are areas navigable by agents that allow the reach of action targets.

Access to the BIM data of the component and the definition of logics and rules for the implementation of properties and functions in the game object, enable the automation of the process of characterizing Static Entities in the simulation environment within the game engine. Once the logic and rules for static entity importation and property application are established, game engines can automate the association and data reconnection process through scripts that utilize BIM component properties (Standard, Link, and Task properties) as mentioned above, ensuring seamless integration of static entities within the simulation environment.

Agents: Agents in the context of construction site simulation represent dynamic entities equipped with intelligence or requiring intelligent control to be moved. These dynamic entities contribute to work activities and may interact with static entities within the construction site environment. Examples include site workers and dynamic equipment that move between different areas of the site to carry out the work, store and retrieve the material or simply reach the toilets or logistics facilities of the construction site.

The 4D BIM model serves as a crucial source of site planning data for the BIM Agent-Based simulation of work activities. In addition to providing 3D BIM data for constructing the simulation environment, the 4D model associates' resources with specific activities from the project schedule. These resources, whether modelled or not, possess properties such as identification, typology, dimension, and cost, contained within the ifc file of the 4D model. These entities are leveraged in many ways within the 4D programming process, to plan their deployment, to verify their positioning and sizing on site, to plan the duration of the activity and to evaluate their cash flow in the construction project. In this study, dynamic site resources are proposed as AI agents for simulating site activities for risk estimation, as explained below.

Agents' generation: The process begins with the generation of the 3D model, where each BIM component corresponds to static entities or 3D Game-Object within the game scenario. These Game-Objects are associated with 4D BIM data structures or external components containing task information, referred to as "*Task properties*" in this context. As indicated before, these data are directly linked to the Game-Objects through scripts and they are stored in external databases, such as files like IFC.

Through scripting or programming logic within the game-engine environment, the resource data associated with each Game-Object is accessed and interpreted to determine the characteristics of the agents to be instantiated, in terms of 3D object in the simulation scenario. This includes attributes such as the number of workers or machines required, types, skills, availability, and spatial coordinates within the scene. Using this resource data, agents representing workers and machines are dynamically created and instantiated within the simulation scenario.

After selecting the scenario and period for analysis (par.5.2.2), the instantiation process of agents by the game-engine script involves analysing the task data of all Game-Objects present in the scene to detect static entities objects relevant to the task. Subsequently, reading the *Task Properties* provides information to access a library of pre-processed 3D object of construction site resources for the appropriate selection of prefabricated 3D models to represent each type of dynamic agent and placing them at specified positions within the scene corresponding to the construction components (Figure 4).

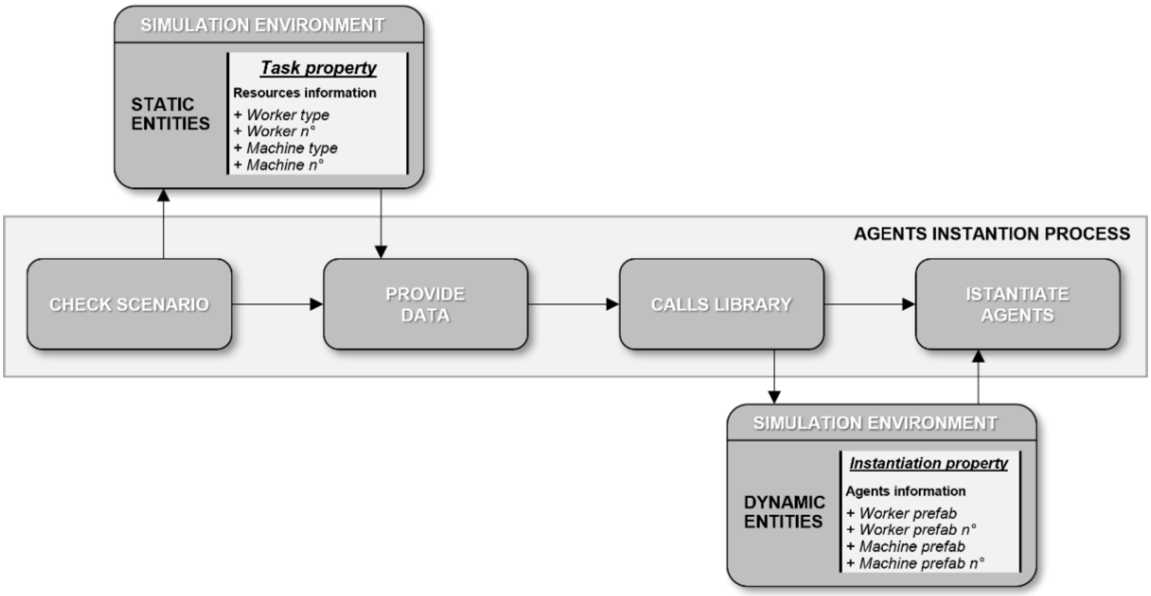

Figure 4: Agents Instantiation Process. The figure outlines the process of creating agents in the simulation environment, starting from the Task Properties of the Static Entities in the agent-based model.

Once instantiated, these agents can interact with the environment, perform construction tasks, move between different locations, and simulate realistic behaviors based on predefined rules or algorithms, as explained below. The simulation can be achieved by incorporating features such as navigation, decision-making systems, task scheduling, visualization of construction progress, interaction detection and visualization of results as indicated below.

***Agents' behavior**:* Studying agents to represent resources behaviours such as humans or machines drive by humans, particularly in the context of workers within construction simulations or other domains, is a fascinating and multidisciplinary topic that intersects various fields such as artificial intelligence, computer science, psychology, and sociology. When considering game engines and game theory, this area of research becomes even more compelling due to the potential for creating immersive and interactive experiences that simulate complex agent behaviors.

In the realm of game engines, agents can be compared to characters, object without intelligence that may be controlled by an intelligent source (i.e. a human player or Artificial Intelligence) in this specific case we have the so-called, Non-Player Characters (NPC), autonomous agents which are controlled by Artificial Intelligence.

These AI agents can exhibit various behaviors, ranging from simple movement patterns to complex decision-making processes. In the context of representing workers in construction simulations, agents could simulate tasks such as construction, maintenance, transportation, communication, and collaboration, contributing to the overall realism and dynamism of the simulation.

In game theory, a theoretical framework is provided for implementing rational decision-makers NPC and for analyzing complex strategic interactions among these rational decision-makers. This can be applied to understand and model human behavior within game engine environments (Dave Mark, 2009). When simulating construction site activities within a game engine environment, several key aspects of agent behavior must be implemented to ensure realism and dynamism:

1) Firstly, agents should be capable of moving efficiently from one target location to another within the virtual construction site, navigating obstacles and adhering to spatial constraints. Movement algorithms such as pathfinding or movement functions that use the same algorithms in a game-engine environment can be employed to calculate optimal paths for agents, considering factors such as terrain topology and dynamic obstacles.
2) Secondly, agents should exhibit lifelike animations corresponding to their actions and interactions within

the environment. Animation blending techniques and motion capture data can be utilized to achieve fluid and natural-looking animations for various activities performed by the agents.

3) Finally, a robust decision-making system is essential for agents to autonomously choose where and when to move based on their goals, objectives, and environmental stimuli. Decision-making algorithms such as finite state machines, behavior trees, or utility-based approaches can be implemented to enable agents to evaluate their options and select appropriate actions in real-time.

By integrating these aspects of agent behavior into the simulation framework, we can create compelling and realistic simulations of construction site activities within the game engine environment.

Sorbi et al., 2022demonstrates the implementation of a simplified behavior model through the incorporation of a decision system in agents just for the choice of the action to be carried out in terms of movement in the 3D simulation scenario, without considering animations and social and psychological aspects. It proposes the implementation of deliberative agents for the agent-based simulation of site activities and suggests developing a BDI architecture using an action planning Utility-system to define the agents' behavior in terms of movement and the Navigation system of Unity Game-engine to perform actions. Combining BDI architecture with utility-based decision-making is a powerful approach for developing AI agent systems that can effectively make decisions and navigate in dynamic environments such as construction sites simulation scenario.

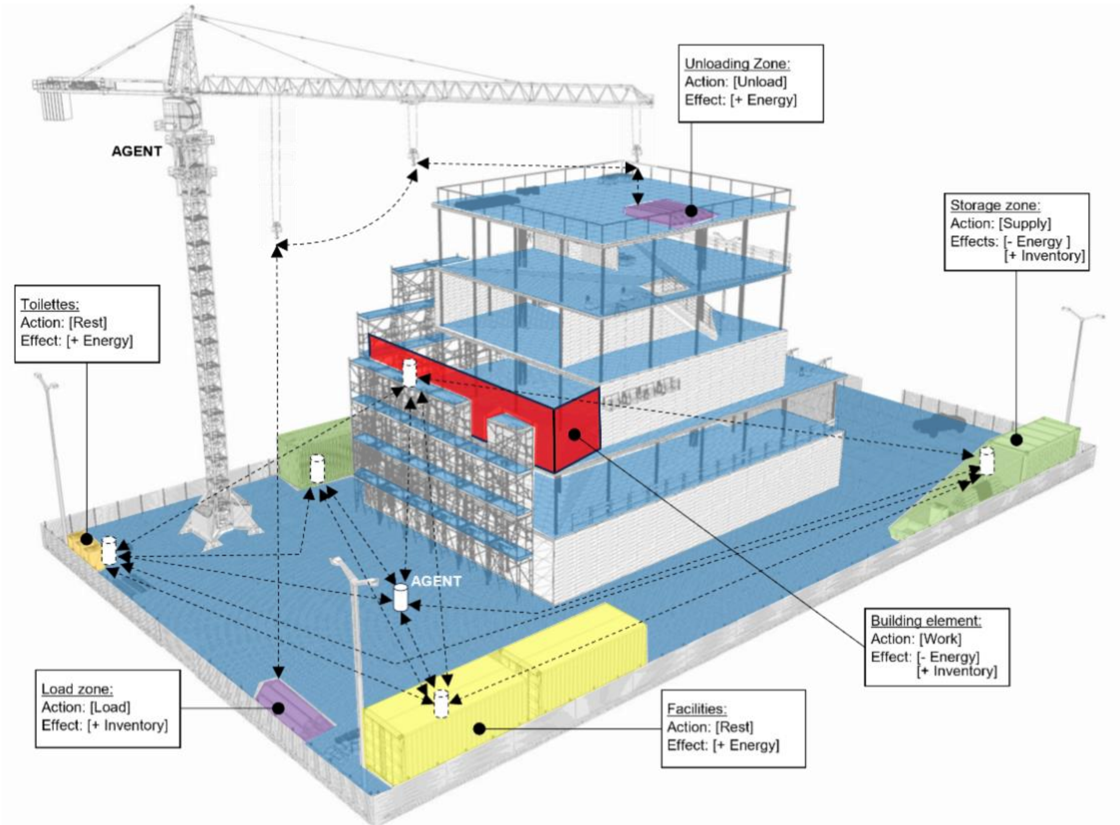

Figure 5: Agents' behavior for autonomous navigation. The figure illustrates how agents navigate and interact autonomously within the construction site, performing tasks such as loading, unloading, working, and resting, while their actions impact energy and inventory levels.

Considering the same hypothesis to omit the more complex and uncertain aspects of human behavior depending on factors such as culture, experience, emotions, character, and many other, and considering as actions, positioning of agents at specific points on the site scenario for each action (Figure 5), a possible implementation of agent behavior for autonomous navigation of site agents in a 3D scenario of the game engine is described below. This system, scriptable into game engines, is based on a hierarchical approach consisting of two levels of decision-making to optimize agent behavior within the construction site environment. At the highest level, agents operate under a Finite State Machine (FSM) framework, where decisions regarding actions are made in real-time based on the agent's current state in the simulation environment. The FSM, starting from the action to be carried out already determined, evaluates whether the agent has reached its destination to perform the intended action, initiates navigation to the designated location for action if necessary. These movements in the construction site simulation scenario are enabled by game engine navigation systems that leverage Navigation Mesh concepts, pathfinding and local avoidance algorithms and dynamic obstacle avoidance, by enabling characters to navigate intelligently and realistically through complex environments. This FSM-based approach ensures efficient and responsive agent behavior, enabling task simulation execution and adaptation to dynamic conditions (Figure 6).

In parallel, the lower level of the system incorporates a utility-based decision-making process to determine the most suitable action for the agent to undertake within the context of its task. In the context of a utility system in game AI or decision-making frameworks, we therefore have the actions as indicated in the example in Figure 5, and for each action we can identify the so-called "*Considerations*" to refer to the factors or variables that are considered when evaluating the desirability or utility of different actions or decisions. Considerations represent the specific aspects of the game state or environment that influence the value or effectiveness of an action. By implementing these factors and variables, defined as "*Consideration value*" in the Figure 7, as characteristics of the agent also defined as "*Internal state*", and extracting a value from the relationship between action and consideration by means of response curves that relate them, the system involves calculating the utility of each potential action based. By integrating these considerations into the utility function, agents can make informed decisions that balance multiple objectives and constraints, ensuring optimal performance during the Agent-Based simulation of site tasks.

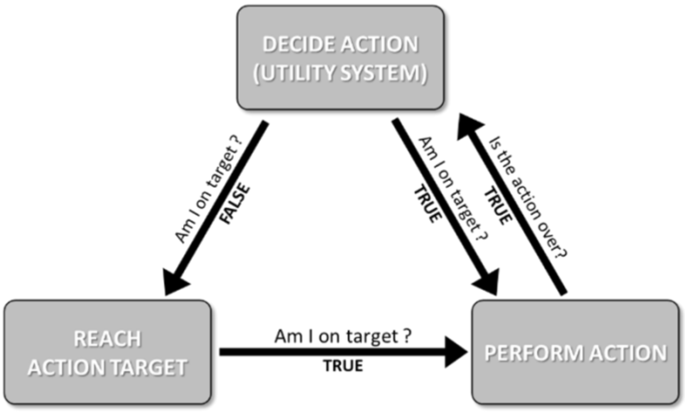

Figure 6: Finite State Machine (FSM) framework for agents' movements. The figure depicts the FSM process guiding agents' actions, including deciding actions, reaching targets, and performing tasks, based on conditions such as target proximity and task completion.

This hybrid approach leverages the strengths of both FSM-based reactive control and utility-based proactive decision-making to enhance the autonomy and effectiveness of agents within the construction site environment. While the FSM framework provides real-time responsiveness and task execution capabilities, the utility system enables agents to prioritize actions strategically, considering long-term objectives and environmental factors. Together, these two levels of decision-making form a robust foundation for autonomous agent behavior, facilitating efficient task execution, coordination, and adaptation within the dynamic and complex construction site environment.

Hazard: In developing an agent-based simulation environment to support risk assessment activity of Safety Manager, it's crucial to thoroughly understand potential hazards within a construction site environment that can be represented in a game engine. To do this, we start from the definition of danger, which is the intrinsic property of the situation, of the substance and of the object, not linked to external factors and which due to its properties or characteristics can cause damage and does not coincide with the risk. Leaving aside the substances for now, we can say that the objects that are a source of danger correspond to machines and equipment used for work activities, in our system represented by agents. From these object dangerous situations related to proximity, contact, or close interaction with the workers, represented as agents in our system. These situations may include scenarios such as collisions between workers and machinery, entanglement hazards, the risk of falling objects, and many more situations. This is the interesting part of the risk assessment (R) which, in addition to the estimation of vulnerabilities (V) and exposure (E) which depend mainly on the type and number of actors or agents in our case, affected by the hazardous situation, must provide a probabilistic value relating to the possibility of occurrence of these hazardous situations (H).

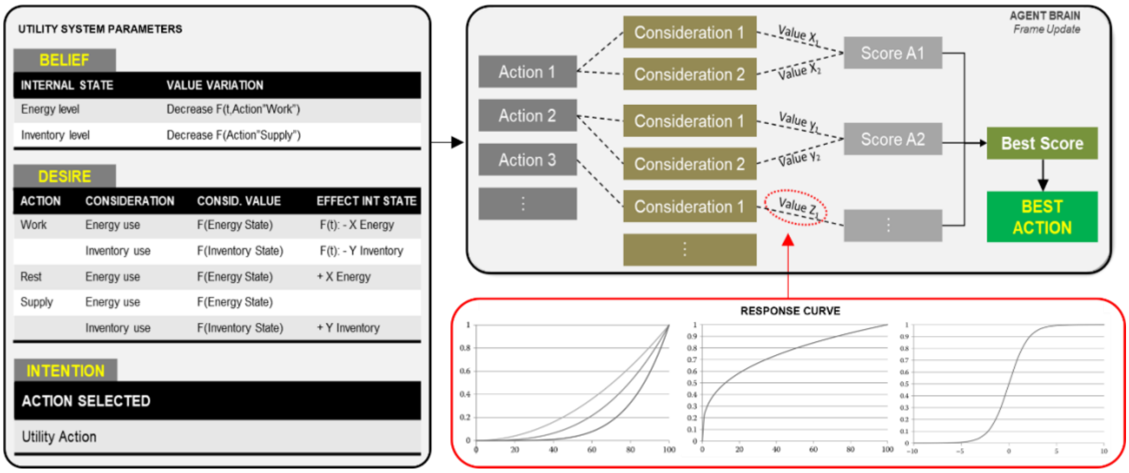

Figure 7: Decision-making system for site agents. The figure illustrates the utility-based decision-making process for agents, including belief states, desires, and intentions, which are evaluated to select the best action based on scoring considerations and response curves.

Agent-based simulation of site activity is well-suited for assessing such hazardous proximity situation due to its ability to model dynamic interactions between agents and their environment. By simulating the behaviors and movements of each individual agents within the construction site, agent-based simulation accurately captures the complexities of on-site operations and interactions, providing data for the estimation of the risk components indicated above. Establishing rules for representing non-tangible object like specific safety/danger spaces related to the activity and site entities (Getuli et al., 2022), exposed or source of hazards, allows for the capture of detailed data on agent behaviors, interactions, and hazards proximity using game methods. This data provides valuable insights into the mechanisms driving risk exposure within the construction site environment.

This approach facilitates the analysis of how proximity to hazards may lead to specific risks and potential accidents, while also enabling the testing of various scenarios and the assessment of safety protocols and interventions. The data-driven insights generated through agent-based simulation aid in identifying critical risk factors and informing proactive risk management strategies.

Thus, the choice of agent-based simulation for assessing risks arising from proximity hazardous situation starting from 4D BIM data, is justified by its ability to provide realistic, dynamic, and data-driven assessments of hazard exposure, ultimately contributing to enhanced safety protocols and risk management practices within construction projects.

5.2.2 Data process

In the development of our framework (Figure 2), the processing of data pertinent to risk analysis (R), that are vulnerability (V), exposure (E), and hazard occurrence (H), constitutes a crucial stage that must take place during the simulation execution. This phase, integral to the simulation's execution, involves the meticulous processing and utilization of data necessary for the comprehensive assessment and recording of simulation dynamics.

Simulation performs: Central to its functionality is the utilization of 4D BIM data seamlessly linked to corresponding Game-Objects within the game engine environment. This integration enables the dynamic reconstruction of construction sequences in alignment with project schedules, offering a visual representation of task progression in real-time.

As previously mentioned, the methodology employed leverages the same principles as BIM 4D simulations, already leveraged for agent deployment. Now the data we are interested in corresponding to the *Task properties* that have not yet been exploited. Again, through scripting or programming logic within the game-engine environment, the *Task Properties* (duration, start/finish date) already associated with each Game-Object is accessed, analyzed, and extracted for storage in data structures sorted by date for easy access during runtime.

At this point, considering the format of the time data of the Task (dd/mm/yyyy, hh:mm), an Absolute Time method appears to be the most suitable for the creation of the time period of the construction in the game engine and for the positioning and setting of the duration of the activities as well as the consequent management of the dynamic and static entities associated with the same task. Through this process, the visibility of the associated Game-Objects is dynamically controlled, ensuring their appearance and disappearance in accordance with the construction schedule (Figure 8).

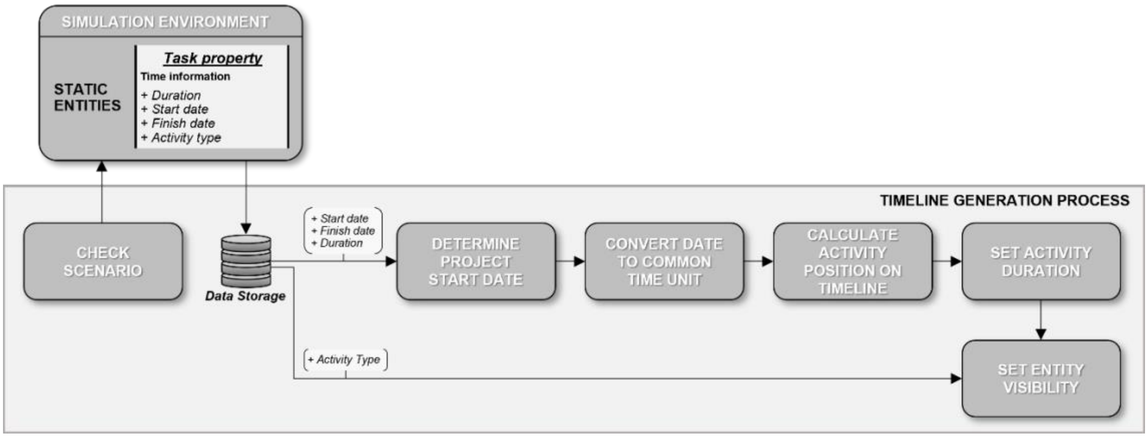

Figure 8: Timeline generation process. The figure describes the process of generating activity timelines in the simulation, starting from the Task Properties of the Static Entities in the agent-based model.

The inclusion of a simulation control panel further enhances the tool's capabilities, providing safety managers with intuitive controls to adjust simulation parameters, manage simulation speed, and navigate the simulation timeline. This level of flexibility empowers safety managers to conduct thorough risk assessments, identify potential hazards, and make informed decisions to enhance safety measures within construction sites. Leveraging the capabilities of the game engine environment and incorporating advanced simulation features, the BIM Agent-Based simulation tool emerges as a valuable asset in the proactive management of construction site safety.

Data collection: Absolutely, detecting collisions or proximity situations classified as hazardous within a game engine simulation is indeed feasible, especially with a focus on proximity hazardous. The game engine environment provides robust capabilities for detecting and responding to such events in real-time. By leveraging the comprehensive knowledge of the simulation environment and its agents, including their spatial coordinates, properties, and behaviors, it becomes possible to implement collision detection algorithms or proximity checks to identify hazardous situations as they occur.

Recording collision data in a game engine involves a systematic process to detect, capture, and analyze collision events within the simulation environment. Initially, collision detection mechanisms are either leveraged from built-in systems or custom algorithms are developed to identify interactions between GameObjects with methods like raycasting, sphere casting, or collision triggers. Upon detecting a collision, the involved GameObjects are identified, typically through collision events or callbacks provided by the game engine. Subsequently, pertinent collision data is extracted, encompassing details such as collision type, the positions GameObjects involved, and any associated properties or attributes. This information is then stored in a suitable data structure or format for subsequent analysis, often involving the creation of data structures or writing to files for storage and retrieval. Optional features like data logging or debugging can be implemented to provide real-time insight into collision events during simulation runs, aiding in debugging and behavior analysis. Finally, aggregated collision data is analyzed to discern patterns, trends, or anomalies, guiding decision-making processes such as adjusting simulation parameters or refining collision detection algorithms. Customization of the collision recording process is often necessary to accommodate specific simulation requirements, considering factors like performance optimization in complex scenarios with numerous GameObjects or frequent collisions. As such, prioritizing efficient data recording mechanisms ensures optimal simulation performance while accurately capturing collision events critical to the simulation's fidelity and analysis.

To extract the objective distribution hazardous events values (H, V, E) to support risk analysis step, a systematic approach is required. This involves conducting multiple simulations with varying parameter combinations and collecting data on hazard occurrences observed during each simulation run. Subsequently, statistical analysis techniques, such as interpolation or regression analysis, can be applied to the collected data to derive objective estimates of hazard occurrence likelihood, vulnerability and exposure values, under different scenarios.

Automatically or manually adjusting behavior parameters at the outset of each simulation allows for the exploration of a wide range of scenarios related to the same activity or period analyzed, capturing variations in agent behavior and environmental conditions. This approach facilitates the generation of diverse datasets, each reflecting distinct combinations of simulation parameters. By recording the data from collision detection or proximity events during each simulation run, comprehensive datasets are compiled, providing insights into the occurrence and nature of hazardous situations. Storing the collected data in separate txt files for each simulation ensures organization and traceability, facilitating subsequent analysis. With each file representing a specific simulation scenario, the data can be easily referenced and compared to identify patterns or trends across different parameter settings.

Subsequently, statistical analysis techniques, such as interpolation or regression analysis, can be applied to the collected data from individual simulation, to derive objective estimates of hazard occurrence probabilities under different scenarios. Interpolating the collected data from individual simulation runs serves to consolidate the findings and derive objective estimates of hazard occurrence likelihood. By synthesizing data from multiple scenarios, interpolation techniques can effectively model the relationship between simulation parameters and hazard occurrences, providing valuable insights for risk assessment and mitigation.

In summary, the proposed approach of adjusting behavior parameters, recording data from simulation runs, storing data in separate files, and subsequently interpolating the data offers a systematic and data-driven method for analyzing hazard and estimate the risk level of each task.

5.2.3 Data Visualization

Combining collision data files related to the same activity or period, analyzing them, and visualizing the results directly on the 3D model in the game engine through heatmaps is a powerful approach to gaining insights into collision patterns and enhancing simulation analysis. By aggregating data from multiple sources and visualizing it in a spatial context, safety managers can effectively identify high-risk areas and prioritize interventions to mitigate potential hazards.

Hazards distribution heatmap: The process begins by reading the collision data files stored from simulation runs corresponding to the desired activity or period. These files contain valuable information about collision events, including affected agents, type of events, location, frequency, and severity of collisions. Leveraging the collision data analysis techniques outlined earlier, such as aggregation and interpolation, the collected data is combined and processed to derive meaningful insights directly in the game-engine.

The next step involves visualizing the combined collision data directly on the 3D model in the game engine using heatmaps. Heatmaps provide an intuitive representation of collision density, with color scales indicating the concentration of collision points in different zones of the construction site. By overlaying the heatmaps onto the 3D model, safety managers can quickly identify areas with the highest risk and prioritize safety measures accordingly.

Several methods exist for developing data visualization in the form of heatmaps within a game engine environment. One approach is to utilize shader-based techniques, where custom shaders are employed to sample collision data and assign colors to vertices or fragments based on collision density. Alternatively, texture mapping can be utilized to overlay a heatmap texture onto the 3D model, with colors representing collision intensity. Particle systems offer another avenue, with collision data used to emit particles at collision points, creating a dynamic heatmap visualization. Procedural generation techniques enable the generation of heatmap-like patterns directly within the game engine, allowing for flexible and customizable visualization. Additionally, external visualization tools can be employed to visualize collision data exported from the game engine, offering advanced features and interactive exploration capabilities, such as the creation of immersive VR scenarios of the construction site simulation (Getuli et al., 2020).

This approach offers several advantages, including real-time visualization of collision data within the simulation environment, allowing for immediate feedback and decision-making. Additionally, the spatial context provided by the 3D model enhances understanding and interpretation of collision patterns, enabling more targeted interventions to improve safety.

Overall, integrating collision data analysis and visualization directly within the game engine environment through heatmaps represents a significant advancement in construction site safety management. By harnessing the capabilities of the game engine, it is possible to provide safety managers with can gain actionable insights into risks, both for risk assessment and to identify any causes, that may be related to layout and schedule choices, and take proactive measures to ensure the safety of personnel and assets on the construction site.

6. CONCLUSIONS

The BIM agent-based simulation system proposed for simulating construction site activity offers a comprehensive solution to support and enhance risk analysis step conducted during risk assessment activity from safety managers. Throughout this study, various aspects of the system have been discussed and there are several benefits that the proposed system can bring, as well as possible limitations.

One of the key advantages of the proposed system lies in its ability to integrate seamlessly with existing BIM workflows, leveraging 4D BIM data to construct detailed simulation environments within a game engine. By simulating construction site activities in a virtual environment, safety managers gain invaluable insights into potential hazards and their likelihood of occurrence. The system's capability to visualize collision data in the form of heatmaps directly on the 3D model enhances understanding and facilitates informed decision-making regarding risk mitigation strategies.

Moreover, the proposed system empowers safety managers to test and validate technical choices related to safety, such as layout and scheduling decisions, in a risk-free virtual environment. By conducting simulations, safety managers can identify high-risk areas, assess the effectiveness of safety measures, and refine construction plans to minimize potential hazards.

However, it's essential to acknowledge potential limitations of the system, such as the accuracy of simulation results and the complexity of integrating real-world data into the virtual environment. Achieving a high level of fidelity in simulation outcomes may require continuous refinement of simulation algorithms and validation against real-world data.

Future developments hold promise for further advancing the capabilities and applicability of the framework. One such avenue for future exploration involves the development of a comprehensive simulation scenario model to rigorously test the application of the proposed framework and methodologies in a controlled environment. This model would allow for the systematic evaluation of the system's effectiveness in simulating construction site activities, estimating the probability of dangerous events, and supporting risk estimation activities conducted by safety managers. By conducting thorough testing and validation, the proposed framework can be refined and optimized to better meet the needs and challenges of the construction industry.

Furthermore, ongoing research and development efforts will focus on enhancing the details and accuracy of simulations, leveraging emerging technologies such as artificial intelligence and real-time data integration to further enhance the utility and effectiveness of the BIM agent-based simulation system in improving safety management practices within construction sites.

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