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CONSTRUCTION SITE PLANNING BY USING ADVANCED SIMULATION METHODS

By

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This work is dedicated to those who made this journey possible, meaningful, and unforgettable.

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Thank you.

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements.

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Abstract

This research proposes the framework of an Advanced Agent-Based Model and Simulation System for site activities risk assessment, starting from 4D Building Information Modeling (BIM) data, to enhance risk management, site planning and scheduling in construction. The construction industry faces distinctive challenges related to worker safety due to its complex, dynamic nature. Traditional safety management methods often fall short in addressing evolving site risks, as they are predominantly reactive and dependent on human expertise, lacking predictive capabilities that could identify risks proactively during the pre-construction phase. This limitation highlights the critical need for data-driven methodologies that enable proactive safety management throughout the construction lifecycle.

The framework utilizes a 4D BIM model, combining spatial and temporal data, to create both the virtual environment and the agents within the simulation. Developed using advanced digital modeling and simulation platforms, specifically Unity, this digital twin accurately represents the construction site layout, schedule, and resources, serving as the foundation for a realistic simulation of site conditions. Within this environment, autonomous agents (representing workers, machinery, and other dynamic elements) are programmed with behavior models to navigate tasks, interact with other entities, and respond to situational changes. This agent behavior captures a range of site activities, allowing for the simulation of real-world scenarios and interactions that generate comprehensive data on site safety dynamics.

During the simulation, detailed data on agent movements and interactions are continuously recorded, providing a basis for calculating key risk factors: hazard likelihood (H), vulnerability (V), and exposure (E). These metrics, derived from observed agents' behaviors such as congestion, proximity to hazards, and task overlap, enable a dynamic and precise risk assessment. By combining these factors, the system calculates the overall risk, visualized through heatmaps that highlight high-risk zones across the site layout. These visual outputs empower safety managers to interpret risk distribution, enabling proactive adjustments to site design, activity sequencing, and resource placement before construction begins. The framework modular structure comprises data acquisition, Agent-Based Simulation, and visualization layers that allow for flexible adjustments as the simulation progresses. Tested in a model scenario, the system demonstrated effectiveness in pre-emptively identifying high-risk zones, supporting safer site layout and task scheduling.

This research makes significant contributions by establishing a model that supports proactive, data-driven decision-making in pre-construction phases. The integration of BIM and ABMS demonstrates the potential for predictive modeling to optimize construction safety management, offering a replicable framework that supports the continuous improvement of safety practices. Moreover, it serves as a practical tool for rigorously evaluating and optimizing pre-construction organizational choices, site layouts, and scheduling strategies, ensuring that these critical decisions are thoroughly tested and validated before construction begins. This proactive approach sets a new standard in construction safety practices, contributing to the continuous improvement of safety management in construction and related fields.

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- **3D BIM:** Three-Dimensional Building Information Modeling
- **4D BIM:** Four-Dimensional Building Information Modeling
- **AABMS:** Advanced Agent-Based Model and Simulation
- **ABM:** Agent-Based Model
- **ABMS:** Agent-Based Model and Simulation
- **AEC:** Architecture, Engineering, and Construction
- **AI:** Artificial Intelligence
- **BDI:** Belief-Desire-Intention (a decision-making model in simulation)
- **BIM:** Building Information Modeling
- **BPMN:** Business Process Model and Notation
- **CSV:** Comma-Separated Values
- **DSS:** Decision Support System
- **E:** Exposure (in risk calculation)
- **FSM:** Finite State Machine
- **H:** Hazard (in risk calculation)
- **H&S:** Health and Safety
- **IFC:** Industry Foundation Classes
- **ISO:** International Organization for Standardization
- **NavMesh:** Navigation Mesh
- **NPC:** Non-Playable Character
- **PPE:** Personal Protective Equipment
- **R:** Risk (in risk calculation)
- **RBS:** Resource Breakdown Structure
- **V:** Vulnerability (in risk calculation)
- **UNI EN ISO:** Italian standard for International Standards Organization standards
- **VR:** Virtual Reality
- **WBS:** Work Breakdown Structure

Glossary

- **4D BIM:** A Building Information Modeling approach that incorporates the time dimension, enabling the integration of construction schedules for improved planning and risk assessment.
- **Activity Manager:** A simulation component that handles schedule data, such as task properties from 4D BIM models, ensuring precise task sequencing and timing.
- **Advanced Model and Simulation Platform**: A sophisticated software environment designed to create, simulate, and visualize complex scenarios, often used for testing and analyzing behaviors within virtual representations of real-world environments.
- **Agent**: An autonomous entity in a simulation, representing a worker, piece of equipment, or other movable element, programmed with specific behaviors and tasked with performing actions within the virtual environment.
- **Agent-Based Model (ABM):** A simulation methodology where agents, representing entities like workers or machinery, interact within an environment to exhibit complex behaviors.
- **Agent Behavior:** The programmed responses and actions of agents within a simulation, enabling autonomous navigation and interaction.
- **Agent Instantiation:** The process of creating and initializing agents in the simulation based on predefined task properties.
- **Bounding Volume:** A 3D shape that encloses an agent or object, used to define interaction zones and detect hazardous interactions.
- **BPMN (Business Process Model and Notation):** A graphical representation used to model business processes, utilized here to illustrate construction safety processes.
- **Collision Detection:** The method of identifying interactions between agents or objects, used to analyze potential risk scenarios in simulations.
- **Collision Trigger:** A simulation feature that logs when two entities come into contact, used for risk assessment.
- **ConstructionManager Script:** A script that populates each 3D static object with task data, organizing data for simulation-based task management.
- **CSV Format:** A standard text format used for data exchange, supporting task property organization and scheduling in 4D BIM.
- **Data Acquisition Layer:** The initial simulation module that gathers and organizes data from BIM models, preparing it for simulation.
- **Data Processing Layer:** A module that records, organizes, and analyzes simulation data related to agent interactions and hazards.
- **Decision Support System (DSS):** A system that assists safety managers by providing insights derived from simulation data for risk management decisions.
- **Dynamic Objects:** Autonomous agents like workers or machinery that move and interact in the simulation according to task requirements.
- **Environment Data Implementation:** The process of setting up the simulation environment, including layout and site entity properties.

- **Exposure (E):** A risk factor measuring how frequently and extensively an entity, such as a worker or equipment, is exposed to hazards.
- **Equipment**: Machinery and tools used on a construction site, such as cranes, excavators, and drills, which are critical for carrying out construction activities efficiently and safely.
- **IfcConverter:** A tool used to preprocess Industry Foundation Classes (IFC) files for simulation, enabling data compatibility in different formats.
- **Finite State Machine (FSM):** A decision-making model for controlling agent actions based on current states in the simulation.
- **Game-Engine**: A software framework designed for creating and managing interactive digital environments, often used in gaming and simulation. Game engines, such as Unity or Unreal Engine, provide tools for rendering graphics, controlling physics, and programming behaviors, enabling the creation of immersive virtual simulations.
- **Game Theory**: A mathematical framework for analyzing strategic interactions among rational agents, where each participant's choices affect the outcomes of others. In construction and simulation, game theory can be applied to model decision-making processes, optimize resource allocation, and predict agent behaviors in competitive or cooperative scenarios on-site.
- **GridManager:** A script in the visualization scene that creates a grid on horizontal planes for localizing and visualizing risk levels.
- **Hazard (H):** The inherent risk potential of an object or situation, which may cause harm in specific conditions.
- **Hazard Identification:** Recognizing potential hazards on a construction site, separate from risk which involves hazard likelihood and exposure.
- **Hazard Space:** A designated buffer area around an agent to prevent hazardous interactions by maintaining safe distances.
- **Heatmap Visualization:** A graphical display of risk levels on the construction site, with color gradients to indicate higher or lower risks.
- **Identity Properties**: Metadata attributes associated with BIM model components, such as name, type, and classification, which uniquely identify and describe each element.
- **Industry Foundation Classes (IFC):** A standardized format for exchanging BIM data across platforms, enabling integration with simulation systems.
- **Interactive Timeline:** A tool for navigating project phases in simulations, allowing parameter adjustments and task progression tracking.
- **Iteration Feedback Loop:** A cycle in simulation to evaluate and adjust safety strategies, refining site planning based on observed outcomes.
- **Link Properties**: Attributes used to connect different BIM model elements, allowing for relationships to be established between components, tasks, or external resources.
- **Navigation Mesh (NavMesh):** A data structure for guiding agents through environments, avoiding obstacles and optimizing movement paths.

- **NPC (Non-Playable Character)**: A simulated character or agent in a virtual environment that interacts with the simulation autonomously, typically used in gaming and simulation contexts to represent entities that are not controlled by users.
- **Orchestrator Script:** A custom script managing agent and task sequencing, visibility of static elements, and dynamic interactions in real-time simulations.
- **Path Tracking:** Recording agent paths to assess exposure to hazards, identifying high-risk areas based on frequent movements.
- **Planning**: The strategic process of defining project goals, setting objectives, and outlining actions and resources needed for construction project execution. Planning focuses on long-term goals and overall project direction.
- **Programming**: The detailed process of organizing specific tasks, allocating resources, and determining timelines for construction activities. Programming translates high-level plans into actionable steps.
- **Proximity Check:** A simulation tool that monitors agent distances from other entities, detecting potential collision risks.
- **Real-Time Clock:** A feature that tracks events independently from the simulation's visual timeline, ensuring accurate data capture.
- **Risk Estimation:** The calculation of hazard (H), vulnerability (V), and exposure (E) values to determine site-specific risk levels.
- **Risk Heatmap:** A visual representation of risk, using color-coded maps to identify high-risk areas based on recorded simulation data.
- **Safety Management**: The systematic approach to managing safety on a construction site, encompassing hazard identification, risk assessment, safety protocol enforcement, and continuous monitoring to protect workers and minimize accidents.
- **Safety Manager**: A designated individual responsible for overseeing and ensuring safety protocols on a construction site. The safety manager conducts risk assessments, enforces safety regulations, and coordinates responses to on-site hazards.
- **Safety Management Team**: A group of professionals, including the safety manager, tasked with developing, implementing, and monitoring safety policies and practices on a construction site. The team collaborates to identify risks, ensure compliance, and maintain a safe work environment.
- **Schedule**: A timeline that outlines the start and end dates for each construction task, including milestones and deadlines. The schedule is crucial for ensuring that the project progresses in an orderly and timely manner.
- **Scenario Data Implementation:** The process of applying 4D BIM scheduling data to the simulation, ensuring accurate agent behaviors.
- **Script**: A set of programmed instructions written in a specific coding language (e.g., C# for Unity) to automate tasks, control behaviors, or manage interactions within a simulation environment.
- **Simulation Scene:** The operational component where agents perform tasks, and data is collected to assess construction site risks.
- **Simulation Properties**: The technical components and settings within a simulation that define how virtual entities interact with their environment and with each other.

- **Site Resources**: Materials, equipment, and human resources required for the execution of construction tasks. Site resources include everything from raw materials to machinery and labor, essential for successful project completion.
- **Static Entities:** Non-movable objects in the simulation, providing a context for agent interactions.
- **Task Properties:** Attributes tied to tasks, such as duration and sequence, informing agents actions and planning in simulations.
- **Utility-Based System:** A decision-making model that helps agents prioritize tasks based on situational needs, enhancing decision accuracy.
- **Virtual Environment Rules:** Guidelines that direct agent actions and interactions to reflect real-world constraints in simulations.
- **Vulnerability (V):** A factor measuring the expected loss or damage when an entity is exposed to a hazard.
- **Work Breakdown Structure (WBS):** A hierarchical project organization tool that structures tasks, aiding in simulation planning.

1 Introduction

1.1 Motivation and background

Construction projects are dynamic processes (Bobick, 2004) that unfold in equally dynamic environments such as construction sites. These sites are distinctly different from other complex work environments, such as those in the industrial sector, due to several unique factors (Rozenfeld et al., 2010). Firstly, construction sites are directly exposed to varying weather conditions, which can significantly impact the progress and safety of the work. Moreover, activities on these sites often interfere with each other, further complicating project management. Another layer of complexity arises from the high reliance on temporary resources. This includes not just the workforce but also equipment, machinery, and materials, all of which are subject to constant change and reconfiguration. This aspect is critical to understand, as it influences both the planning and execution phases of a project. Additionally, the physical layout of a construction site is in a state of continuous evolution. It changes over time and assumes different configurations, which are influenced by various factors. These include morphological changes, such as alterations in the structure or form of the building being constructed; topographical shifts, which refer to changes in the surface features of the site; and topological variations, encompassing the spatial relationships and arrangements of the site components.

Understanding these multifaceted challenges is essential for effective construction project management. It requires a comprehensive approach that considers not just the technical aspects of construction but also the environmental, logistical, and human factors at play. Effective management of these variables is crucial for the timely, safe, and cost-effective completion of construction projects. Directly related to this complexity is the safety management, or rather the safety of the construction site and the workers who live on it, is an important aspect of the success of a project, being able to have a clear positive or negative influence. Optimal safety management can promote and optimize the success of the project, while problems related to problems such as accidents and injuries seriously risk complicating the final success of the project. Safety within a construction project, encompassing both the security of the site and the well-being of the workers, is a pivotal aspect that can significantly influence the project's success. Effective safety management has the potential to not only prevent accidents and injuries but also to foster a productive and positive work environment. This, in turn, can lead to improved efficiency and morale, ultimately contributing to the overall success of the project. On the contrary, neglecting safety measures can have dire consequences. Accidents and injuries on the and construction site not only jeopardize the health safety of the workers but also disrupt project timelines, increase costs due to delays and legal liabilities, and can damage the reputation of the companies involved. Furthermore, frequent incidents can lower worker morale and productivity, further hindering project progress.

Therefore, optimal safety management should be viewed as an integral component of project management, and given the natural characteristics of the construction site, a different, more adaptive strategy is required to effectively pinpoint potential safety issues and manage risks. Despite the considerable studies and developments in the field of analysis, monitoring, and alerting real time systems during construction phase, also based on Artificial Intelligence (AI) (Section [2]), a conventional approach in pre-construction step to identifying hazards and risks often proves insufficient. New approaches should emphasize proactive hazard identification, where risks are anticipated and addressed before they manifest into incidents. This is possible through the activity of site and safety design and planning and scheduling of work activities. To achieve this, it could involve the integration of advanced modelling and simulation methodologies and systems.

It's widely acknowledged that the adoption of Building Information Modeling (BIM) has sparked a transformative shift in the construction industry, fundamentally altering the way projects are designed, planned, and managed. BIM offers a comprehensive digital representation of a structure's physical and functional attributes, going beyond mere 3D modeling to encompass an entire process that enhances collaboration, communication, efficiency, and precision across the construction lifecycle. In addition to its role in design and planning, BIM holds significant promise for safety management within construction projects. Through 3D and 4D modeling, BIM provides a potent means of visualizing the construction process over time, allowing for the sequencing of tasks, resource allocation, and the coordination of various activities on-site. This capability is instrumental in enhancing safety protocols. Research in the use of BIM for bolstering construction site safety is a relatively recent but swiftly expanding application. It encompasses a broad spectrum of considerations, ranging from site layout planning and logistics to the identification and mitigation of potential hazards, even extending to training initiatives aimed at improving worker safety awareness, as better described in Section [2.2]. Overall, the integration of BIM into construction processes represents a pivotal advancement not only in terms of efficiency and accuracy but also in promoting a safer working environment for all involved parties. On the flip side, there exist robust predictive analysis methodologies that harness advanced simulation systems. These systems are adept at forecasting future events or behaviors by considering a multitude of parameters, data inputs, and algorithms. They serve as sophisticated computational tools, capable of modeling and predicting outcomes across various scenarios in intricate environments, employing diverse methodologies to simulate real-world processes, behaviors, or systems. These simulations find extensive application across sectors such as healthcare, medicine, aviation, automotive, economics, defense, and numerous others. By conducting analyses and tests within entirely digital environments, they facilitate decision-making grounded in data analysis and scenario planning. This becomes particularly crucial in instances where real-world testing proves too risky, expensive, or entirely unfeasible, such as in the situation of hazards and risks assessment that workers could encounter on specific construction sites.

This study endeavors to establish a novel proactive methodology for conducting risk analysis and evaluating the site design choices and activity planning during pre-construction step. It proposes integrating 4D Building Information Model (BIM) with Agent-Based Simulation to support the risk assessment of on-site activities, leveraging advanced modeling and simulation tools. By combining these technologies, the aim is to develop the frameworks for the development of an advanced simulation tool for the risk estimation through ABS of BIM-based site activities. This integrated approach holds promise for improving overall construction site safety measures and pre-emptively addressing risks before they manifest on the job site.

1.2 Objectives and research questions

The intricate and dynamic nature of construction sites, characterized by the involvement of multiple entities and constantly evolving spatial configurations, poses significant challenges to Health and Safety (HS) management. Traditional risk assessment methods, which predominantly rely on human expertise, often fall short in accurately predicting and mitigating potential hazards inherent to these dynamic environments. Manual approaches may overlook certain risks, increasing the vulnerability of sites to accidents. This gap underscores the urgent need for novel methodologies that harness advanced technologies to bolster safety management, a need further elaborated upon in Section [2].

Reflecting on the literature review and analysis, this research is founded upon three pivotal principles:

- *Objective:* This research aims to support safety managers in the critical risk management tasks during the pre-construction phase. The goal is to enhance and optimize site and activity planning to improve worker safety and increase construction site productivity.

- *Approach:* The proposed solution is the development of an Advanced Agent-Based Modeling and Simulation (AABS) system for construction site activities. This system is designed to assist safety managers in estimating risk during the pre-construction phase. By analyzing data generated from Agent-Based Simulations of construction site activities, the system will provide risk forecasts contextualized to a 3D construction site environment. These forecasts will be presented in the form of heatmaps, highlighting critical and hazardous areas on the construction site caused by improper site design choices or inadequate activity planning. The AABS system aims to produce predictive risk maps that can be used to assess the overall effectiveness of site design and activity planning, as well as to identify areas where safety measures and procedures may need to be integrated or improved.

- *Methodology:* This study advocates for the use of advanced modeling and simulation techniques to proactively identify risks in phase of planning. The proposed system involves the development of a 3D Agent-Based Simulation platform derived from 4D Building Information Modeling (BIM) data. By leveraging advanced modeling and simulation methods, the research seeks to utilize 4D BIM data to recreate 3D digital scenarios that reflect planned construction site conditions. Autonomous agents, representing site entities (e.g., workers, machinery, materials), will be implemented in the simulation model, each with decision-making behaviors, to simulate site activities. These simulations will be used to calculate risk levels (in compliance with UNI standards) and to visualize risk distribution through heatmaps displayed on the 3D model.

In addressing the complexities involved in developing a support system for risk analysis of construction site activities, this study is guided by the following research questions (RQs), aimed at bridging current knowledge gaps, and introducing innovative solutions:

RQ1: "How can the risk management process for safety managers in construction sites be enhanced by integrating 4D Building Information Modeling (BIM) and Agent-Based Simulation?"

RQ1 delves into the effectiveness of combining these technologies to provide a comprehensive and dynamic analysis of safety hazards, discussed in Section [4] following a foundational literature review in Chapter 2 and an exploration of relevant domain and processes in Section [3].

RQ2: "What are the essential components and potential challenges in developing a system that effectively combines 4D BIM and Agent-Based Simulation methods and technologies for use in construction site risk management?"

RQ2 centers on identifying the crucial components and potential challenges in devising a system that seamlessly integrates 4D BIM with simulation technologies for enhanced safety management in construction. It investigates the essential elements, technical necessities, and potential hurdles involved in creating such a system, considering the practicalities of deploying it in real construction settings. The response to this query, outlined in Section [5], unveils the comprehensive architecture of the proposed framework, detailing its features, operations, interrelationships, dependencies, and mode of implementation.

RQ3: "What impact does the implementation of this AABMS system for site activity risk assessment have on the effectiveness of safety management practices in construction projects, and how can its success be measured?"

RQ3 focuses on evaluating the impact of implementing this integrated 4D BIM and advanced simulation system on the efficacy of safety management practices in construction projects and establishing methods for measuring its success. It aims to appraise the practical application of the system, its role in enhancing safety management, and how its effectiveness and contributions to minimizing safety risks can be quantified. The outcomes of applying this system in a test site environment for evaluation and analysis are presented in Section [6].

This framework aims not only to improve construction site planning and construction projects, providing a dynamic and predictive approach to the risk management, but also to serve as a model for integrating new technology into risk management practices in industries like construction site, from the planning phase. In addition, this research seeks to contribute to the theoretical understanding of risk management in dynamic and complex environments, emphasizing the importance of advanced simulation and data-driven decision-making. The methodology to be adopted, which will be detailed in the following sections, is designed to comprehensively address these questions through practical applications and empirical analysis.

1.3 Thesis methodology and structure

This thesis systematically explores the development of a proactive risk assessment system for construction sites by integrating Building Information Modeling (BIM) with Agent-Based Modeling and Simulation (ABMS). The objective is to simulate site activities with agent-based modeling, identifying hazardous situations and obtaining detailed risk information directly from these incidents. This information is then visualized in the construction environment through heatmaps, which contextualize risk by mapping it onto the physical setup, site organization, and the planning and scheduling of activities. This approach provides a dynamic and spatial understanding of risk, enabling safety managers to view risk information within the actual site layout and operational plan, thus supporting targeted safety interventions and improved safety planning.

The journey begins with a **comprehensive review of the literature** in Section [2], establishing a context for the research and underscoring the need for more dynamic, predictive safety measures in construction. The review identifies gaps in current safety management approaches and explores how BIM and ABMS technologies are emerging as promising solutions to these challenges. The chapter also introduces specific open issues, forming the basis of the thesis objectives.

Section [3] lays out the **theoretical framework** that underpins the system. This includes defining key concepts of risk and hazard as they apply to the construction context, particularly focusing on the unique challenges of predicting and managing risks in complex site environments. Additionally, the chapter delves into the principles of 4D BIM and ABMS, which together form the core methodology for simulating and assessing risks.

The development of the system itself is detailed in Section [4], where the focus shifts to the **integration of BIM and ABMS for risk analysis**. This chapter explains the workflow for setting up a 4D BIM project and describes the steps required to create a realistic simulation environment that can respond to site-specific risk factors. Through this integration, the thesis demonstrates how predictive modeling can enhance safety management by providing real-time insights into potential hazards.

In Section [5], the thesis outlines the **system architecture** designed to support a structured approach to safety analysis. This architecture divides the system into modules and layers, ensuring that each element—from data acquisition to risk visualization—is organized to maximize both functionality and clarity. This structure enables construction managers to simulate site safety scenarios and make proactive decisions based on accurate, real-time data.

Section [6] presents the **test case and results**, applying the developed system to a sample construction site model. Here, the thesis demonstrates the system’s effectiveness in identifying and visualizing high-risk areas, particularly those prone to collision or impact risks. The results are presented in heatmaps, which graphically show areas of high risk, validating the system’s practical application. This chapter concludes with a discussion of the system’s performance, highlighting areas for improvement.

Finally, Section [7] **concludes** with reflections on the contributions of the research, summarizing its implications for construction safety management. The thesis ends by discussing limitations and identifying areas for further research, emphasizing potential enhancements to the methodology and opportunities to refine the integration of BIM and ABMS in broader construction applications.

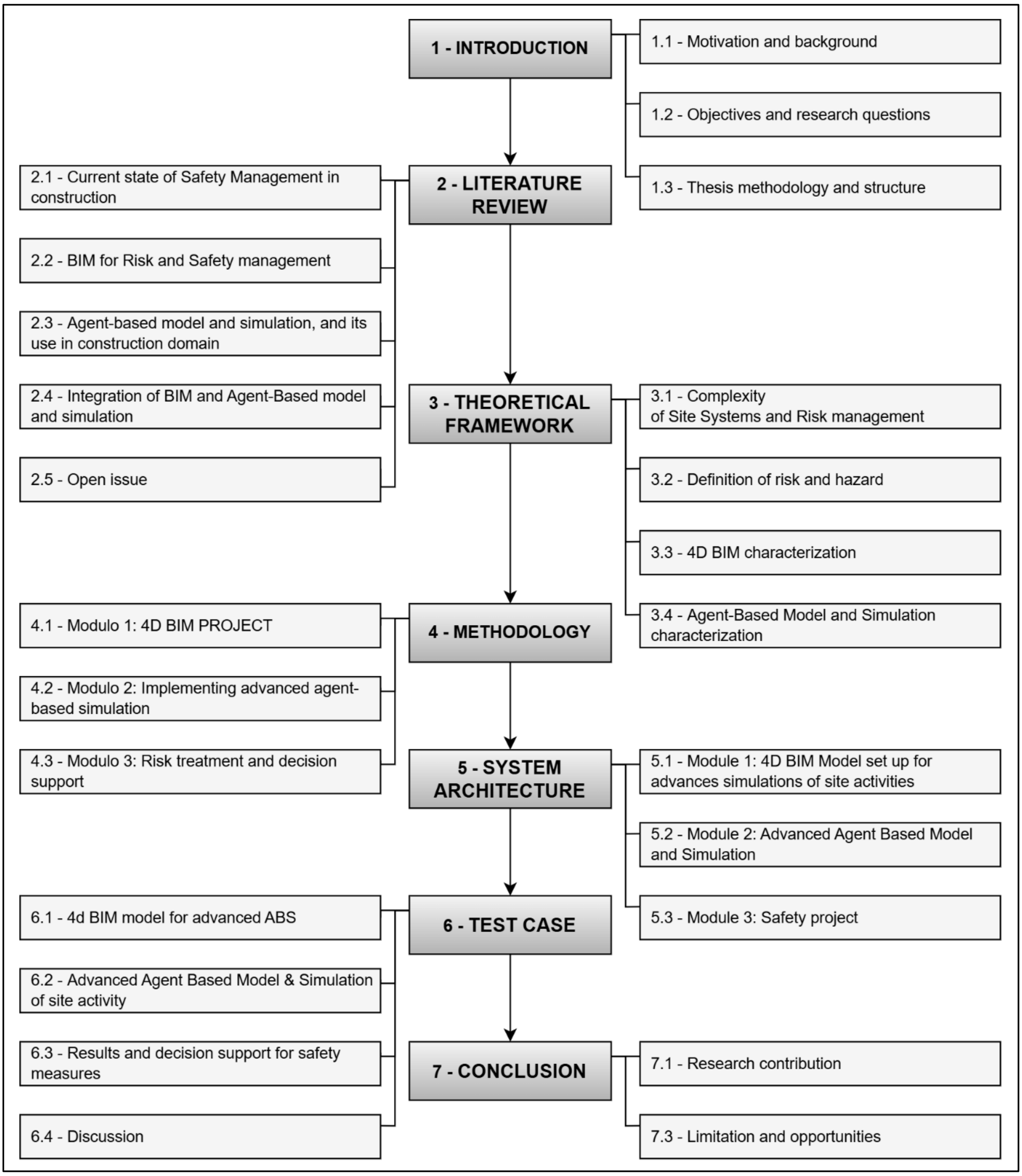


Figure 1 – Thesis Structure and Chapter Outline

2 Literature review

This chapter presents a comprehensive and critical examination of the literature, underpinning the research framework and the development of a novel system that integrates Building Information Modeling (BIM) and Agent-Based Simulation for enhanced safety management in construction projects.

Section [2.1] delves into the existing practices and regulatory standards governing the construction industry. It critically analyzes the prevalent hazards and accidents characteristic of construction sites, exploring their underlying causes. This analysis extends to a detailed review of current safety management strategies, highlighting their effectiveness and limitations. This evaluation serves as a baseline for understanding the conventional approaches to safety management in construction and sets the stage for discussing the need for more innovative and proactive methods.

Section [2.2] Here, the focus shifts to Building Information Modeling (BIM), a transformative tool in the construction sector. This segment explores the innovative practices in BIM, both emerging and established, that significantly enhance safety management on construction sites. The discussion will cover the evolution of BIM from a mere modeling tool to a comprehensive safety management facilitator. It will also shed light on how BIM is reshaping the landscape of construction safety, facilitating a shift towards more proactive and preventive safety strategies through its advanced modeling capabilities.

Section [2.3] investigates the realm of (advanced simulation environment) Agent-Based Modeling and Simulation, emphasizing its application in the construction industry. This part will explore the theoretical foundations of agent-based models, their versatility, and how they can be effectively utilized to simulate complex interactions and scenarios in construction projects. The focus will be on understanding the potential of these models in predicting and mitigating site-specific hazards, thus contributing to a more informed and dynamic approach to safety management.

Section [2.4] culminates with an in-depth exploration of the synergistic integration of BIM and Agent-Based Simulation systems. This section will analyze the existing methodologies and technologies facilitating this integration, highlighting their strengths, limitations, and potential for innovation in construction safety management. The discussion will extend to the practical aspects of implementing such an integrated simulation tool, considering the technological, organizational, and human factors involved in its adoption and use in construction environments.

Finally, the chapter culminates with a comprehensive summary summarizing the main findings and unresolved issues arising from the literature review. This summary not only encapsulates the knowledge gained from current practices, advancements, and applications in the realms of BIM and Agent-Based Simulation in construction safety management, but also critically addresses the open questions and knowledge gaps that emerged from this analysis. These unresolved questions represent crucial areas for further exploration and innovation that have fuelled research goals and questions.

2.1 Current state of safety management in construction

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 and economic development of the country (Ruddock & Lopes, 2006). However, the construction sector still presents today critically in terms of safety and accident, despite there has been a substantial globally improvement in occupational safety and health in the construction sector, generally motivated by the publication, implementation and continuous updating of standards by the most relevant international organizations for the sector (BS OHSAS 18001[1], ILO-OSH 2001[2], ISO 31000 [3], ISO 45001[4], etc) increasingly stringent regulations (Sousa et al., 2014).

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. One of the most important factors able to affect the efficient and safe delivery of construction projects is the site workspaces availability (Dawood et al., 2005). 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 assessment (Sorbi et al., 2022).

One of the most important factors that can adversely influence the H&S conditions on site is the workspace configuration. Space is a limited resource on a construction site. Workers, equipment, facilities, and material storage areas require different spaces, and they compete with each other for space usage. Moreover, the space requirement of a construction activity is dynamic, i.e., the geometry and the location of the workspace continuously change over time throughout different phases of the construction activity, leading to a sequential series of workspaces that are associated with the construction activity (Getuli et al., 2020). In addition to this, the presence of dynamic resources such as heavy equipment, vehicles and materials, that works in proximity to workers can cause hazardous situation, increasing the risk of injuries and fatalities for construction personnel (Marks & Teizer, 2013). Given the inherent complexity and hazardous nature of the construction industry, particularly during the execution phase, considerable efforts have been directed towards the enhancement of safety management practices, both in academic research and industry practice. Over the past few decades, the field of construction safety management has undergone significant

[1] OHSAS 18001 is the acronym for Occupational Health and Safety Assessment Series (OHSAS). It is the British standard that defines a specific management system for workers' health and safety, referring to the BS OHSAS 18001:1999 standard, issued by BSI (British Standards Institution) in 1999, revised in 2007 (BS OHSAS 18001:2007), and replaced by the ISO 45001:2018 standard.

[2] ILO-OSH 2001 is a guideline developed by the International Labour Organization (ILO) that provides a framework for implementing an occupational health and safety management system. It promotes a continuous improvement approach to prevent workplace accidents and occupational diseases.

[3]ISO 31000 'Risk management -- Principles and guidelines' is a guide that provides general principles and guidelines for risk management. It can be used by any public, private, or social organization, association, group, or individual, and is not specific to any industry or sector.

[4] "ISO 45001 'Occupational health and safety management systems – Requirements with guidance for use' is an international standard that specifies the requirements and guidance for the use of occupational health and safety management systems. It enables workplaces to be safe and healthy, prevents work-related injuries and health issues, and proactively improves OHS.

evolution, incorporating advanced methodologies, technologies, and management frameworks to mitigate risks and safeguard workers.

Historically, construction safety management primarily focused on regulatory compliance and reactive incident management. However, the strengthening of both local and international regulatory frameworks, coupled with the implementation of more stringent safety protocols, has led to a paradigm shift towards proactive risk management. This contemporary approach emphasizes the anticipation and prevention of accidents before they occur. Consequently, research has increasingly adopted a holistic and integrated perspective, with key areas of focus including:

- **Design for Safety (DfS):** A growing body of literature (Che Ibrahim et al., 2022; J. Gambatese & Hinze, 1999; Hallowell & Hansen, 2016) has un-derscored the importance of integrating safety considerations during the design phase of construction projects. This approach, known as Design for Safety (DfS), actively involves architects, engineers, and contractors in identifying potential risks at the early stages of project planning and design. Research indicates that the early integration of safety measures can significantly reduce the likelihood of accidents during the execution phase, underscoring the critical role of design in enhancing safety outcomes on-site.
- **Technological Innovations:** Technological advancements have emerged as key enablers of improved safety management in construction. Innovations such as Building Information Modeling (BIM), drones, wearable sensors, and augmented reality are being employed to monitor site conditions, facilitate real-time communication, and provide hazard detection in dynamic environments. BIM allows for the simulation and visualization of construction processes, enabling project teams to proactively identify and mitigate potential risks in a virtual setting before they materialize in the physical workspace (Azhar et al., 2008; Kim et al., 2013; Kunz & Fischer, 2020; Silva et al., 2022; Wang, 2013).
- **Behavioral Safety and Safety Culture:** Recent studies (Berglund et al., 2023; Choudhry, 2014; Dester & Blockley, 1995; Him et al., 2023; Wamuziri, 2006) have highlighted the critical role of behavioral safety and the establishment of a robust safety culture within construction organizations. Safety programs that focus on worker behavior, attitudes, and engagement have demonstrated positive outcomes in reducing unsafe practices. The role of leadership and management in cultivating and sustaining this culture is increasingly recognized as pivotal in achieving long-term safety improvements. A strong safety culture not only fosters adherence to safety protocols but also promotes active participation in continuous safety enhancement.

Although progress has been made in the areas of behavioral safety and safety culture, future research is expected to focus on the development of predictive management systems (Ding et al., 2012; Esmaeili et al., 2015; Esmaeili & Hallowell, 2012; Khan et al., 2019; Lv et al., 2023; Ning et al., 2018) aimed at anticipating risks during the pre-construction phase, particularly in the planning, scheduling, and design of the construction environment. This proactive approach is essential for addressing risks that arise during the organization and execution of construction activities, ensuring that safety is prioritized well before work begins.

Predictive management systems, enhanced by artificial intelligence (AI), machine learning, advanced modeling and simulation technologies, and data analytics, will be critical in identifying potential hazards related to site logistics, activity sequencing, and resource allocation during the pre-construction phase (Toğan et al., 2022). These systems will enable project planners to simulate and forecast risks based on historical, synthetic, and real-time data, allowing them to optimize schedules and workflows to minimize exposure to hazards. Technologies such as Building Information Modeling (BIM) and digital twins will become indispensable tools during this phase, providing highly detailed virtual representations of construction sites that allow for the design and optimization of layouts, material storage areas, and traffic flows (Martínez-Aires et al., 2018). By simulating site logistics and spatial configurations, planners can swiftly identify safety issues related to the movement of personnel and equipment, ensuring that the construction environment is designed with safety as a priority from the earliest planning stages (Abune'meh et al., 2016). Furthermore, technologies such as augmented reality (AR), sensors, and IoT-based systems will complement these predictive tools by providing real-time data and insights during the construction phase (Getuli et al., 2021; Hasan et al., 2022; Natephra & Motamedi, 2019). The integration of predictive safety systems with advanced site modeling will enable project teams not only to prevent accidents but also to create safer and more efficient workflows throughout the planning and scheduling phases.

By focusing on the pre-construction phase, particularly on the planning, scheduling, and design of the construction environment, future research will drive the development of predictive systems that anticipate risks and enhance safety management. This will lay the groundwork for a more proactive and technology-driven approach to safety management in the construction industry.

2.2 BIM for risk and safety 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. (S. 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., 2017a). 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(Tak et al., 2021; Zhou et al., 2013). 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 4D Bim models (Moon 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), 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).

2.3 Agent-Based Model and Simulation, and its use in construction domain

Recent advancements in computer simulations, driven by increased computational power, have enabled the development of more accurate modeling techniques that closely resemble real-world systems. One such powerful simulation approach is agent-based modeling (ABM), which has been increasingly applied across various phases of the construction process, particularly in solving problems during the construction phase. The effectiveness of ABM in simulating on-site activities has been demonstrated in numerous studies, which have utilized it to enhance equipment operations and improve safety protocols during construction (Marzouk & Ali, 2013; Younes & Marzouk, 2018). Given the intrinsic link between worker safety and site productivity, ABM has gained traction for its ability to model the behavior of construction laborers and teams, considering their social and cognitive interactions. Studies have shown that ABM can effectively simulate the dynamics between workers, foremen, and managers, and its role in improving safety outcomes has been well documented (Binhomaid, 2019; Goh & Askar Ali, 2016). By incorporating the social-cognitive aspects of construction crews, ABM enables researchers and practitioners to better understand how safety behaviors evolve in response to management strategies and interpersonal interactions.

The potential of ABM extends beyond safety protocols and productivity. It has been applied to simulate the cognitive and social processes influencing workers' safety behaviors. For example, ABM has been used to explore how interactions between workers and management affect adherence to safety practices. This sociocognitive approach highlights the role of social identity and peer influence in reducing unsafe behaviors on site (Ye et al., 2020). Additionally, ABM has been employed to analyze how social norms and group dynamics impact safety outcomes, further emphasizing the importance of behavioral modeling in construction safety management (Ahn & Lee, 2015). The growing availability of ABM-specific software, capable of integration with widely used platforms like BIM and CAD, has further driven the adoption of ABM in both academic research and practical applications. These tools enable researchers to simulate and verify design choices, allowing for a deeper understanding of occupant behavior and response to various scenarios, such as evacuations in complex environments, whether on a construction site (Marzouk & Daour, 2018) or in other settings like conference halls (Bina & Moghadas, 2020).

In conclusion, ABM continues to provide a robust framework for modeling and enhancing both safety and productivity on construction sites. Its ability to simulate real-world interactions, consider social-cognitive factors, and integrate with advanced design tools positions it as a key technology in the future of construction safety and operations management.

2.4 Integration of BIM and Agent-Based Model and Simulation

The integration of Building Information Modeling (BIM) and Agent-Based Modeling and Simulation (ABMS) has garnered increasing attention in scientific research due to the complementary nature of these two methodologies. BIM offers detailed digital representations of the physical and functional characteristics of buildings, while ABMS simulates the behavior and interactions of individual agents (such as workers, occupants, or equipment) within these environments. The integration of ABMS into BIM environments has shown significant potential in improving construction site management and safety. For example, researchers have used ABMS to simulate worker-management interactions, allowing for the assessment of various safety management strategies on workers' performance. Through these simulations, different managerial scenarios were analyzed, offering valuable insights into how different strategies could help mitigate safety risks on-site (P. Zhang et al., 2019). Additionally, as already described in Section [2.2], a framework was developed integrating ABMS with BIM to simulate labour evacuation in construction projects, demonstrating the capability of ABMS to model emergency evacuation scenarios, thereby enhancing pre-construction safety planning (Marzouk & Daour, 2018).

In the context of BIM-based design workflows, studies have shown the importance of social interactions and information flow dynamics. By using ABMS and social network analysis, researchers were able to simulate the interactions between project stakeholders, highlighting that while BIM enhances workflow efficiency, its full potential is realized when effective collaboration and communication are present. This integration allowed for a more dynamic exchange of information, reinforcing the importance of human factors in optimizing BIM's collaborative potential (Al Hattab & Hamzeh, 2018). BIM has become widely used for architectural design, construction simulation, and workflow optimization, yet the integration of human behavior simulation remains underexplored. To address this gap, researchers have developed models linking BIM with agent-based behavioral simulation engines, allowing for simulations of occupant interactions, movements, and behaviors. This approach significantly enhances building design by incorporating human factors, improving not only the functionality but also the safety and usability of the built environment (Cheng & Vincent J. L., 2013).

Further advancements have been made by transitioning from static BIM models to dynamic simulations of building use. This approach integrates ABMS to simulate user interactions and behaviors over time, offering a more comprehensive view of building functionality and performance. By extending BIM's traditional scope, these simulations provide insight into how buildings are actually used, supporting the long-term evaluation of building designs (Simeone et al., 2017a).

2.5 Open issue

The integration of Building Information Modeling (BIM) and Agent-Based Simulation (ABS) offers substantial potential to enhance construction safety, especially in protecting workers and improving site safety. By simulating human interactions, equipment movements, and space dynamics, BIM-ABS integration allows for a proactive approach to risk management, identifying potential hazards and inefficiencies during the early stages of construction planning. This predictive capability is particularly valuable in preventing accidents before they occur, helping safety managers and project planners create safer work environments. However, despite these advancements, several critical open issues persist, particularly concerning the tools available to safety professionals during the preconstruction phase. One of the most significant challenges is the lack of advanced support tools that enable safety technicians and planners to evaluate project designs from a safety perspective using predictive and preventive analyses. The current technology landscape often lacks intuitive and accessible systems that can simulate safety risks in the preconstruction phase, leaving safety evaluations to be reactive rather than proactive. This limits the ability of project teams to fully assess how design choices, activity sequencing, and site logistics will impact worker safety once construction begins.

Moreover, the integration of BIM models with ABS frameworks is complex and often difficult to implement in large-scale projects. Ensuring seamless data exchange between these systems is essential for accurate simulations of site conditions and worker behaviors, yet this interoperability remains an ongoing technical challenge. As project size and complexity increase, so too do the variables that need to be considered in safety simulations, making real-time analysis more difficult and less reliable. This challenge underscores the need for better scalability in simulation tools to address the increasing complexity of modern construction projects. Furthermore, many of the current tools for ABS are not designed with ease of use in mind. Safety managers and site technicians, who are often the first line of defense in protecting workers, need more intuitive interfaces that allow them to implement these technologies effectively. Tools that provide real-time feedback, simulate safety scenarios, and offer clear insights into the safety implications of design choices could empower these professionals to make better, faster decisions aimed at preventing accidents and improving overall safety performance.

Addressing these gaps will require concerted research and development efforts focused on creating more accessible, scalable, and standardized safety tools that fully integrate BIM and ABS capabilities. The overarching goal of this research is to develop a comprehensive framework for an advanced simulation system that integrates Building Information Modeling (BIM) with Agent-Based Modeling and Simulation (ABMS) to facilitate proactive risk estimation and improve safety management in construction projects. Specifically, this framework will focus on the preconstruction phase, addressing the need for advanced tools capable of evaluating construction site layouts, work sequencing, and spatial dynamics with a focus on safety.

To achieve this objective, the research will concentrate on identifying the critical requirements and key elements necessary for the successful integration of BIM and ABMS in the construction safety domain. This involves a detailed analysis of how BIM's detailed spatial modeling capabilities can be enhanced through the inclusion of Agent-Based Simulations, allowing for dynamic modeling of worker behavior, equipment movement, and site logistics. By doing so, the framework will enable construction planners and safety managers to assess, in a proactive manner, potential risks associated with specific site configurations and activity sequences long before work commences. The framework will also outline the fundamental steps required to implement such a system, including the development of scalable data integration protocols between BIM and ABMS, the creation of user-friendly interfaces for safety professionals, and the establishment of standardized criteria for validating and testing simulation outcomes. Each of these steps will be systematically analyzed to ensure that the final system is both practically applicable and theoretically robust, capable of addressing the complex, dynamic, and hazardous nature of construction environments.

To validate the proposed framework, a preliminary test model will be developed and employed to simulate real-world construction scenarios. This model will serve as a proof of concept, demonstrating the system's ability to predict and mitigate site-specific risks by simulating worker interactions, equipment movements, and space requirements, providing data to evaluate the effectiveness of the planning and scheduling project of the construction site and of the individual work activities in the pre-construction phase. Ultimately, this research aims to contribute to the field of construction safety by offering an innovative, technology-driven approach to risk management. By integrating BIM and ABMS, the proposed system will enable a shift from reactive safety management to a proactive, predictive model, ensuring that safety is embedded into the very fabric of project planning and execution. The insights gained from this study will also provide a foundation for further advancements in simulation technologies, paving the way for more comprehensive safety systems in construction and beyond.

3 Theoretical framework

3.1 Complexity of site systems and risk management

Effective risk management in construction presents a multifaceted challenge, largely due to the inherent complexity and dynamic nature of construction sites. These environments are constantly evolving, with continuous changes in activities, resources, and personnel. This dynamic nature creates unique challenges for risk management, requiring ongoing attention and adaptation to the multitude of interacting entities and evolving conditions. These intrinsic characteristics place the construction sector at the top in terms of worker injuries and illnesses worldwide. In Italy, according to the latest data published by INAIL[5], the sector remained second only to manufacturing in terms of lives lost in 2022, with 175 deaths, a 16% decrease from the previous year, marking the lowest number of work-related deaths in the past five years. Most occupational injuries (62%) and deaths (55%) occur during demolition/preparation phases, electrical and plumbing work, and specialized construction activities, with the remainder occurring in building construction and civil engineering works (INAIL (National Institute for Insurance against Workplace Injuries), 2023).

Globally, within the EU, the construction, transportation and storage, manufacturing, agriculture, forestry, and fishing sectors accounted for approximately two-thirds (65.5%) of all fatal work-related injuries in 2021, and nearly half (45.7%) of all non-fatal work-related injuries. Over a fifth (22.5%) of all fatal work-related injuries in the EU occurred in the construction sector, highlighting the high-risk nature of the industry (Eurostat (Statistical Office of the European Union), 2023).

In the United States, since 2008, the construction industry has experienced more total deaths than any other industry, with 1,056 of the 5,486 fatal injuries recorded in 2022 occurring in construction (U.S. Bureau of Labor Statistics (BLS), 2023). Analyzing more specifically the types of hazards that most affect a construction site, the U.S. BLS attributes most fatal incidents in the construction sector to two major hazard groups:

- **Falls (from the same level or to the ground)**: responsible for 423 of these fatalities. The fatality rate for this occupation group increased from 12.3 deaths per 100,000 FTE workers in 2021 to 13.0 in 2022.
- **Contact with objects and equipment:** despite general improvements in fatal statistics between 2018 and 2021, there was a notable increase in fatal events in the last year. Over 50% of recorded incidents were due to being struck by non-transport vehicles or struck by falling objects or equipment.

[5] INAIL (National Institute for Insurance against Workplace Injuries) is an Italian public institution that insures workers against occupational injuries and diseases, providing compensation, promoting prevention, and supporting rehabilitation and reintegration into the workforce.

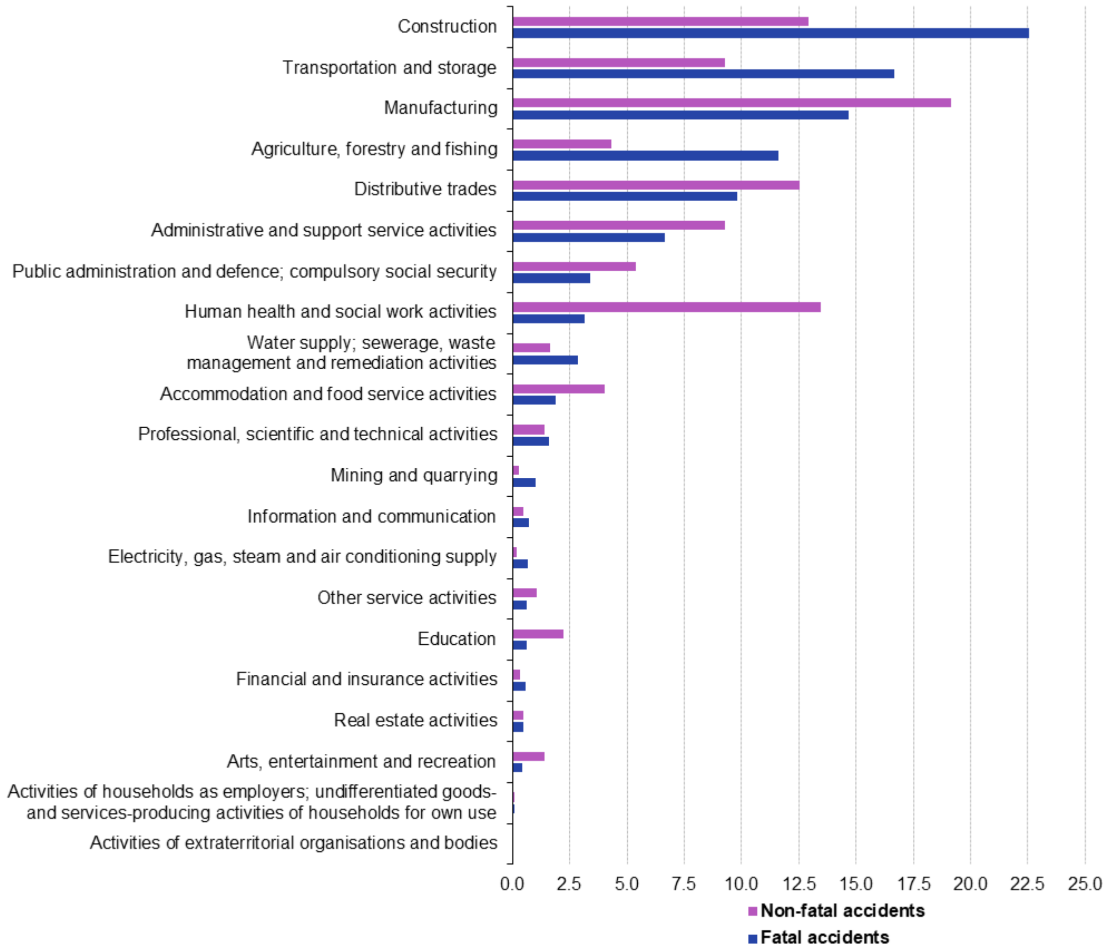


Figure 2_Fatal and non-fatal accidents at work by NACE section, EU, 2021, (% of fatal and non-fatal accidents). *Source:* Eurostat (hsw_n2_01) and (hsw_n2_02)

The data show a propensity for dangerous events in construction sites that are severe enough to cause death attributable to space activity conflict and unsafe work condition. Setting aside multiple factors that certainly influence human psychology and hazardous behaviors, from a technical perspective, these two problems can be attributed to:

- **Limited spaces:** suboptimal layout organization and design of construction site spaces.
- **Multiple concurrent activities and sub-activities**.
- **Variety and complexity of resources** (of different types) operating or temporarily present on the site.
- **Dynamic and continuously evolving** work environment and scenarios experienced by workers.
- **Stochastic elements** (e.g., weather conditions, soil characteristics, road accidents, etc.)

This complexity to manage interactions in the construction site system with sites characteristics results in a significant challenge for safety managers from the design and planning phases of construction projects. The design of construction site layouts and safety plans is essential for an effective integrated process but is traditionally performed through error-prone and inefficient manual observation. Moreover, building designers and health and safety coordinators still lack a collaborative working approach (Getuli et al., 2017b).

Predict and understanding these dynamics is crucial for identifying potential hazards and implementing effective safety measures for project success and achieving objectives. In recent years, safety performance has become more recognized in the construction industry, as studies have shown that hazardous work environments can significantly impact schedule and budget performance. Due to the high direct and indirect costs associated with accidents and hazardous conditions, research into construction safety risks is essential to improve the overall performance of construction projects (Hallowell & Gambatese, 2008). The planning and design phases offer an opportunity to eliminate hazards before they appear on the job site, and this ability diminishes as the project progresses. A significant portion of the ability to positively and effectively influence construction site safety is lost when safety considerations are delayed until the construction phase (Gambatese et al., 2008).

Despite their crucial role in worker safety, designers often lack awareness of their influence and the relevance of their role in safety. Although there are delays and difficulties in implementing "prevention through design" in design structures, regulations define specific roles and expertise in safety that come into play not only during construction but also from the planning phase of the work. In accordance with the definition in Section [3.2], risk assessment in the AEC context is a logical, systematic, and comprehensive approach to identifying, analyzing, and treating risks, playing a crucial role in planning the work environment, activities, and work schedule. However, traditional risk assessment methods, heavily reliant on human expertise, often struggle to address the complexities of construction site dynamics. Manual methods may not accurately predict or prevent potential hazards, leaving sites vulnerable to accidents. Additionally, although these methods are important techniques for risk management, they are confined to static control management and play only a limited role in practice. Traditional risk management implementation remains a manual task, with assessment heavily reliant on experience and mathematical analysis, and decision-making often based on intuition, leading to decreased efficiency in real environments (Shim et al., 2012). Therefore, innovative approaches leveraging advanced technologies are urgently needed to enhance safety management.

3.2 Definition of risk and hazard

Con l’obiettivo di sviluppare un sistema di simulazione avanzato basato su agenti, sfruttando i modelli BIM 4D, per supportare i manager della sicurezza cantiere, nell’attività di risk assessment, è fondamentale comprendere la definizione di rischio in termini H&S dei lavoratori, in order to avoid potential confusion. Today, in the construction industry, the concept of risk is adopted in many different fields and with a variety of different words, such as “hazard”, “threat”, “challenge” or “uncertainty”. However, it is very important to distinguish the meanings of risk and danger as indicated below in the definitions relating to the international standard ISO 31000 and the Italian national standard on safety in the workplace Legislative Decree 81/08 (Table 1). 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 likelihood that an event capable of causing damage in that specific context will occur.

Factor	*UNI EN ISO 31000:2018*	*D.Lgs. 81/08*
Hazard	*Generally, the concept of hazard in relation to risk can be interpreted as a potential source of harm.*	*Intrinsic property (of the object, situation, substance, etc.) not linked to external factors that has the potential to cause injuries to people, damage to property, or some kind of economic or environmental loss.*
Risk	*The "effect of uncertainty on objectives," where the effect is a deviation from what is expected, positive or negative. Risk is therefore understood as a measure of the hazard likelihood and consequences of failing to achieve set objectives.*	*The possibility that a given hazard may cause harm under specific conditions of exposure. It is often quantified by assessing the likelihood and consequences of such harmful event.*

Table 1 - Hazard and Risk definition

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. 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, in planning phase, hazards transition into risks is challenging but crucial for safety management. It involves identifying or predict hazardous situations and implementing safety measures.

Central to the risk management process (Figure 3), valid in all sectors, indicated by the ISO 31000:2018, is the comprehensive identification of potential risks and hazards present in the construction environment. Placing the topic in a construction site environment with reference to the safety of workers during work, 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.

Figure 3 – Risk Management Process

Once hazards are identified, the next step is to assess their potential impact on worker safety. Risk assessment involves in the risk analysis. This phase consists of the sizing of the risk, the UNI EN standard defines the risk through the combination of 3 variables:

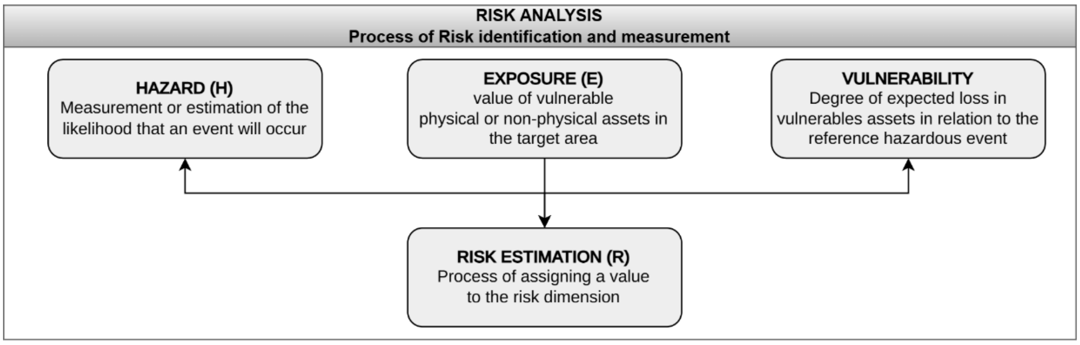


Figure 4 - Risk Analysis Process

- H – HAZARD: Measurement or estimation of the likelihood that a hazardous event has of occurring. Likelihood (e.g., probability) that a reference hazardous event of a given intensity occurs within a given period in a target area.
- V – VULNERABILITY: Degree of expected loss in one or more vulnerable assets in relation to the reference hazardous event. How vulnerable the structures and workers of the construction site are to a collapse.
- E – EXPOSURE: value or numerical consistency of vulnerable physical or non-physical assets in the target area. For example, the number of people, facilities and equipment exposed to the risk.
- R – RISK = P x V x E: Expected value (within a given period) of vulnerable physical or non-physical assets lost as the result of the occurrence of a reference hazardous event

Risk assessment involves evaluating the likelihood and severity of potential incidents resulting from these hazards. By quantifying the level of risk (R) associated with each hazard, safety manager and construction stakeholders can prioritize their efforts and allocate resources effectively to mitigate the most critical risks first. Following risk assessment output, many preventive, protective and control measures are implemented to minimize or eliminate identified hazards. From the analysis of the risk variables, in a construction site environment, influencing factors has been ordered into 3 macro-categories of specific conditions, as shown in Table 5.

1	SITE ENVIRONMENT CONDITIONS
The conditions of the site environment and the work area play a crucial role in the safety of the construction site, influencing the likelihood of accidents. A well-designed layout of the construction site, which provides adequate space for the movement of equipment and people, can significantly reduce risks. The overlapping of activities must be carefully planned to avoid dangerous interference between different operations. Additionally, weather conditions can have a significant impact: rain, high winds, or fog can increase the risk of slipping, falling, or losing control of machines. Therefore, it is essential to constantly monitor the weather and adjust activities accordingly to ensure a safe and well-organized work environment.	
2	WORKERS' CONDITIONS
Workers' conditions include several factors that affect their vulnerability and their ability to perform tasks safely. Their physical and mental state, spoken language, and understanding of safety instructions are key elements.	

Specific training and continuous training are essential to ensure that workers are aware of the risks and know how to behave in dangerous situations. The proper use of personal protective equipment (PPE) is equally crucial, as these tools provide a physical barrier against many hazards. The experience of workers in the specific sector and their familiarity with the operating procedures and equipment used are determining factors in the prevention of accidents.	
3	EQUIPMENT CONDITIONS
The condition of the equipment is a fundamental aspect of safety on the construction site, directly influencing the likelihood of failures and accidents. The density and amount of equipment in use must be managed to avoid congestion and reduce the risk of collisions or interference between machinery. Regular and thorough maintenance of equipment is essential to ensure its functionality and operational safety. Equipment should be inspected frequently for defects or signs of wear and tear that could compromise its safe use. Finally, proper management and strategic placement of equipment within the construction site help to create a safer and more organized work environment, minimizing risks to workers and facilities.	

Table 2 – Influencing Factors of Site Safety

The safety manager, in the planning phase, finds himself evaluating these three conditions relating to the work activity and intervenes in the following two ways:

- Prevention measures, both behavioral (training, information, correct use, etc.) and technical and organizational (implementation of specific technologies and devices, work planning, organization of activities, access limitation, etc.)
- Protection measures, both individual (personal protective equipment) and collective (barriers, parapets, etc.).

So, in addition to defining more consolidated aspects regarding the correct behaviors and procedures to be maintained on site and in the use of specific devices and equipment, the safety manager, aiming to reduce estimated risk levels, implements these measures through design choices in the construction site setup and program that directly impact project objectives and worker safety. These measures can be categorized as indicated in Table 3.

PLANNING AND SCHEDULING OF CONSTRUCTION ACTIVITIES:	DESIGN OF CONSTRUCTION SITE LAYOUT	ORGANIZATION OF SPECIFIC ACTIVITIES:
***Chronoscheduling of Work Activities**: Timing and duration of each task to ensure optimal workflow.* ***Work Breakdown Structure (WBS)**: Organizing tasks into manageable sections to enhance focus on safety.* ***Sequence and Constraints**: Order of operations and constraints that influence task execution.* ***Relations**: Interdependencies among various tasks and their impact on overall safety.* ***Weather Conditions**: Consideration of environmental factors that can affect safety on site.*	***Spatial Arrangement**: Designing the layout to maximize efficiency while ensuring safety.* ***Paths and Practicability**: Safe and clear paths for movement around the site.* ***Signage**: Appropriate signs to guide and inform workers about hazards.* ***Technologies**: Adoption of modern technologies to enhance safety and communication.*	***Designated Spaces and Limits**: Defining specific areas for tasks to control work environment.* ***Bans and Restrictions**: Prohibitions and limitations on certain activities to prevent accidents.* ***Equipment**: Ensuring the availability and proper use of safety equipment.*

Table 3 - Construction Site Safety Measures

As demonstrated, risk analysis is a complex activity that involves multiple aspects listed above that affect the level of risk of a construction site activity. 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. However traditional risk assessment methods remain confined to static control management and play only a limited role in practice (Zhang et al., 2014), and heavily reliant on human expertise, often struggle to address the complexities of construction site dynamics.

There is a need to develop a proactive risk estimation system that is able to process the complexity of a construction site scenario, providing useful information about risks level and for the evaluation of the construction site design measures defined in the pre-construction phase. This work aims to answer this question with the development of a framework for an advanced simulation system that allows the evaluation of the design aspects of construction site in relation to the risk levels of the various activities, already in the design phase. The idea pursued is to exploit, through advanced modeling and simulation platform, the planning and project data contained in 4D BIM models, first for the creation of construction site scenarios corresponding to a specific period of the works, then for the implementation of intelligent agents, in terms of human resources and equipment. Agent simulation is particularly useful for modeling complex systems where risk often arises from interactions between agents or between agents and the surrounding environment such as the construction site. This system will allow safety experts to carry out a forecast assessment of the progress of the construction phase through ABMS where, the recording, analysis and visualization of the data collected on interactions in the scene, observing the collective behaviors and emerging phenomena resulting from the choices of construction site of the work.

3.3 4D BIM characterization

Building Information Modeling (BIM) is a methodology that employs digital models to represent the physical and functional characteristics of a building. This technology plays a critical role in construction projects as it allows for the integration of all necessary information into a single digital model. This integration facilitates preventive analyses and evaluations for the phases following the design process. As discussed in Section [2.2] of the Literature Review, BIM has significantly transformed the approach to design, including safety considerations.

In the context of BIM, 4D modeling introduces the time dimension to traditional 3D models. This addition not only represents the building's geometry but also incorporates temporal information that aids in planning and managing construction activities. Site planning through 4D BIM enables the setting of detailed models and management of information content for Work Breakdown Structures (WBS), as well as the management of material resources, equipment, and machinery. Furthermore, it allows for the design of site layouts for different construction phases, optimizing space and resource utilization.

A 4D model provides a visual simulation of construction sequences planned by the designer. This simulation proves invaluable for forecasting, planning, and visualizing workflows, materials, and costs throughout the construction process. The temporal visualization helps in identifying potential conflicts or inefficiencies early on, allowing for modifications to the construction plan before issues manifest on the actual site.

Consequently, the 4D model becomes a powerful tool for improving project management, reducing risks, and enhancing the prediction and control of costs and timelines.

Traditional 4D design and simulation are typically limited to managing 'known' data, sequentially organizing the construction of resources across various site configurations. However, this approach does not simulate the dynamic activities of essential entities such as workers and machines, whose interactions create complex dynamics that are difficult to predict in intricate systems like construction sites. The current research aims to overcome these limitations by using 4D models as a starting point for advanced simulations, which assess not only the sequence of activities but also how workers and machines influence risk levels and overall site safety. ABMS simulation enables the exploration of emergent behaviors and responses to unforeseen changes with a flexibility lacking in classical 4D simulation. Integrating 4D model data with Agent-Based Simulation provides a more comprehensive and dynamic view of the project, combining the accuracy of traditional planning with the adaptability and realism of simulated interactions.

3.4 Agent-Based Model and Simulation characterization

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. In addition to BIM concepts, new simulation methods and the use of game engines have seen a significant increase in their adoption in the construction sector even for the aspects of site safety management.

Simulations are fundamental tools used across various fields to predict, analyze, and understand the behaviors of complex systems. Typical applications of simulations range from engineering to finance, meteorology to traffic management, and from biology to social sciences. The primary advantages of simulations include the ability to explore hypothetical scenarios without the costs and risks associated with real-life experiments, the capacity to analyze emergent behaviors in complex systems, and the opportunity to optimize processes and strategies. However, simulations also have some limitations: they can be computationally intensive, require accurate and complete data to be effective, and sometimes may be too simplistic to capture all the nuances of a real system. In this context, Agent-Based Modeling and Simulation (ABMS) emerges as an advanced technique that addresses many of the challenges posed by traditional simulations.

Analyzing the developments in the industrial sector, particularly in facilities known as factories, it is evident how these are adapting to new production demands such as the shift to electric manufacturing, increasing demand for raw materials, and growing environmental sustainability requirements. To tackle these changes, industries are investing in the development of digital twins of their plants, or virtual factories, to leverage new opportunities from planning to operations. A virtual factory is a physically accurate representation of a real factory. These digital twins enable manufacturers to model, simulate, analyze, and optimize production processes, resources, and operations without the need for a physical prototype or pilot plant (James McKenna, 2024).

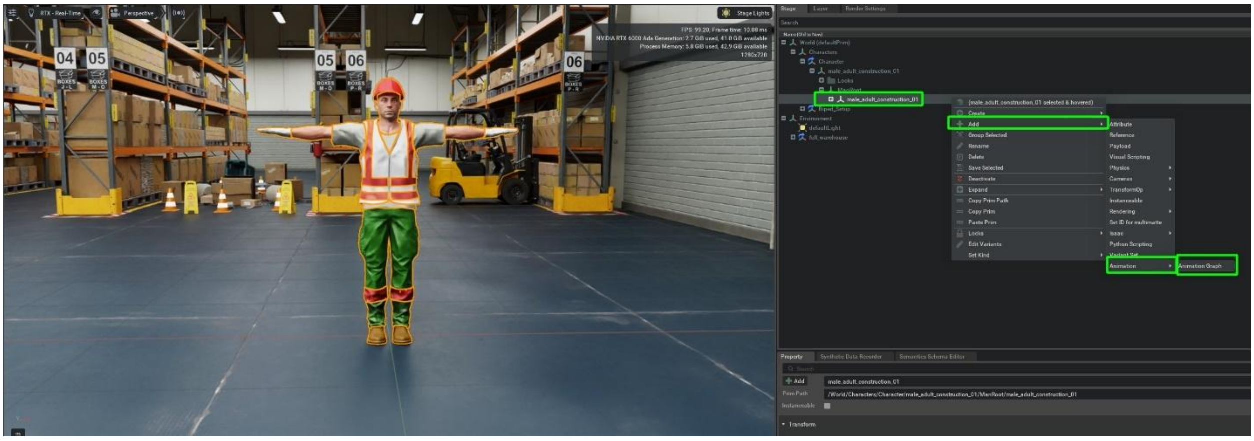


Figure 5 - Example of a digital twin of a factory with autonomous agents representing workers and machines processed with the NVIDIA Omniverse platform

The same approach can be applied to the construction sector through the creation of digital twins of construction projects (4D BIM), integrated with autonomous agents corresponding to workers and machines (ABMS). This research proposes a framework for the creation of an advanced simulation system for construction site activities. The 4D BIM model, which digitally represents the geometry, resources, and temporal sequence of construction activities, is utilized to create an accurate and dynamic virtual environment. In this environment, utilizing ABMS concepts, it is possible to implement autonomous agents that can perform construction activities, realistically simulating daily operations. These autonomous agents, interacting among themselves and with the simulated environment, generate valuable data on emergent behaviors and efficiencies or inefficiencies of the construction project. This data allows technicians to test their construction choices and assess the associated risks and risk levels, giving them the ability to make informed decisions based on predictive data derived from situations and behaviors that are difficult to predict without such systems, especially in particularly complex environments.

ABMS was involved as it represents a modeling and simulation methodology in which a system is modeled as a collection of autonomous agents interacting with each other and with their surrounding environment. Each agent is programmed with a set of specific rules and behaviors that allow it to make decisions and act independently. This distinctive characterization makes ABMS particularly suitable for studying complex systems where emergent dynamics are the result of interactions among multiple components. Agents can represent a wide range of entities, from individual humans (such as workers and machines in our case) in a human population, to animals in an ecosystem, or robots in an automated factory. Each agent is characterized by specific attributes and follows defined behavioral rules, which may include decision-making processes, learning and adaptation mechanisms, and interactions with other agents and the environment. These features allow agents to respond dynamically and adaptively to the changing conditions of the system.

One of the fundamental aspects of Agent-Based Modeling and Simulation (ABMS) is its ability to model emergent phenomena—complex behaviors that cannot be predicted by merely analyzing individual system components. For instance, in a model simulating urban traffic, the individual decisions of drivers (agents) can lead to the emergence of traffic jams or regular traffic flows, depending on behavioral rules and environmental conditions. This level of detail and realism allows for the exploration of 'what-if' scenarios and the assessment of the impact of various policies or interventions.

Similarly, in an ABMS model applied to a construction site, the individual decisions of workers and the use of machines can generate complex site dynamics. Workers (agents), by following specific safety and operational rules and interacting with heavy machinery, can significantly influence site efficiency and safety. These interactions may lead to the emergence of efficient work patterns or, conversely, increased risks and operational inefficiencies (Figure 6). Like urban traffic, using ABMS in a construction site setting allows for the simulation of various 'what-if' scenarios to evaluate the impact of different site configurations, the introduction of new technologies, or changes in safety protocols, enabling engineers to optimize both productivity and safety during the design phase.

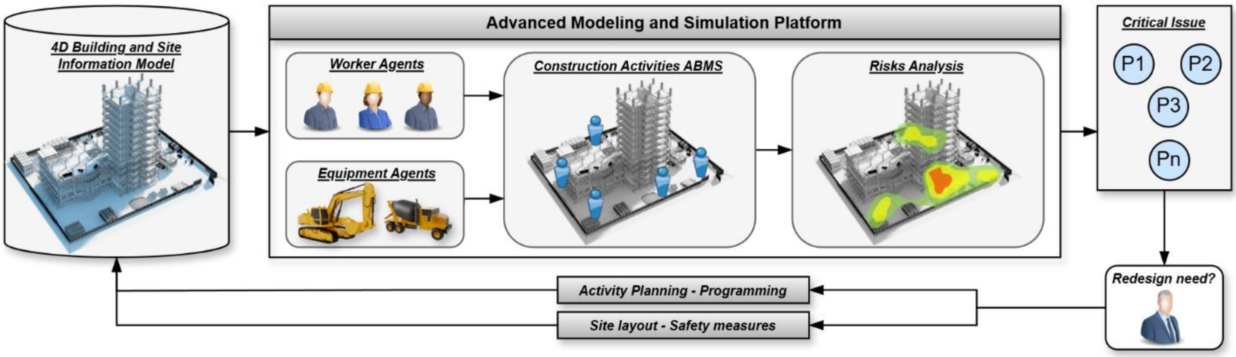


Figure 6 – Proposed Application of ABMS to Construction Sites for Activities Risk Analysis and construction project validation

The characterization of Agent-Based Modeling and Simulation (ABMS) also stands out for its flexibility and scalability. Agent-based models can be developed and implemented with varying degrees of complexity, from simple models featuring a few agents and basic rules to highly sophisticated simulations involving thousands of agents with complex behaviors. This scalability makes ABMS an extremely versatile methodology, suitable for a wide range of applications from social sciences and ecology to logistics, emergency management, and construction. The rapid advancement of computing technologies has further enhanced the capabilities of ABMS. Increases in computational power and the development of advanced software tools, such as agent simulation platforms (NetLogo, AnyLogic, GAMA) characterized by user-friendly interfaces, predefined libraries of agent-based behaviors, and advanced visualization capabilities, or platforms for advanced modeling and simulation (Unity, Unreal Engine, NVIDIA Omniverse, etc.) that allow the implementation of immersive and interactive virtual environments for the realistic simulation of complex system dynamics, have enabled the creation of increasingly complex and detailed models, facilitating model development and analysis.

In conclusion, Agent-Based Modeling and Simulation represents a powerful and flexible methodology for studying complex systems. The ability to model emergent dynamics, the flexibility in defining agent behaviors, and the scalability of the simulation make ABMS an indispensable tool in many fields. With the ongoing development of computing technologies, the significance and applicability of ABMS are set to increase, offering new opportunities for understanding and managing complex systems in an increasingly realistic and detailed manner.

4 An Advanced BIM and Agent-Based Simulation system for risk analysis: Methodology

This chapter introduces an innovative framework that combines Building Information Modeling (BIM) with Agent-Based Modeling (ABM) to advance risk analysis in the management of construction site safety. The framework is designed to support safety managers by enhancing risk assessment capabilities and validating choices regarding construction project and site setup in the pre-construction planning phase.

The research develops a sophisticated Agent-Based Simulation using data from a 4D BIM model. This approach generates a detailed digital twin of the construction site, where autonomous intelligent agents—representing workers, machines, and equipment—execute simulated activities. This simulation captures predictive data crucial for forecasting work progress and estimating potential risks associated with work activities.

The primary objective is to produce heatmaps indicating hazardous events risk level directly on the model through estimation of the likelihood of hazard occurrences (H), Vulnerability (V) and Exposure (E) from the recorded data relating to the hazardous events that occurred during the simulation. This information is intended to be easily visualizable and interpretable by technicians, providing a comprehensive assessment that goes beyond mere risk values. It evaluates the effectiveness, functionality, and impact of decisions related to site setup, organization, and activity planning. These elements crucially influence the three major risk factors: work environment conditions, worker conditions, and equipment conditions, as elaborated in Section [3.2].

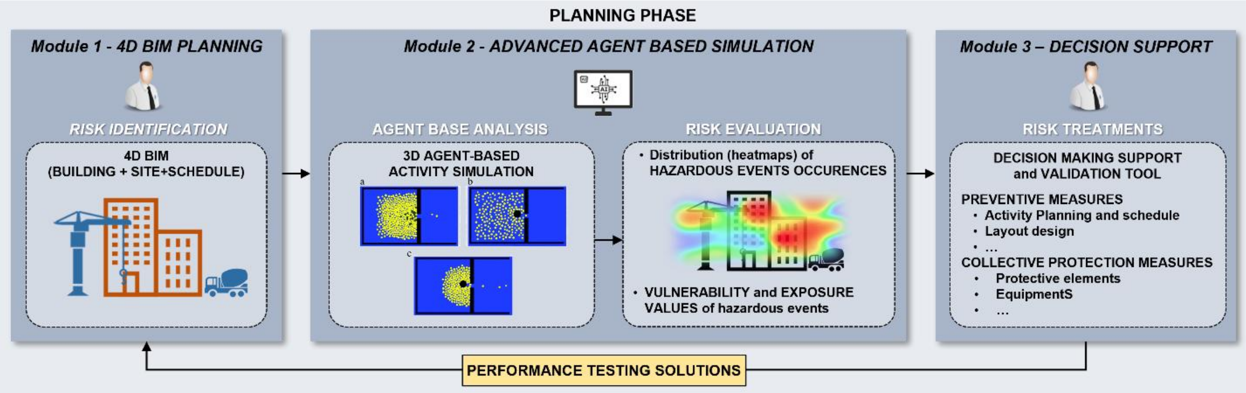


Figure 7 - Framework of Advanced BIM & Agent-Based Simulation for risk assessment of site activities.

As illustrated in Figure 7, this research outlines three modules, each contributing unique aspects 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. Starting with BIM programming of the intervention, the Advanced Agent-Based Model and Simulation System supports the risk analysis phase by providing valuable information for subsequent phases of risk assessment. These modules collectively form a comprehensive framework aimed at enhancing risk management practices within the construction industry and optimize in the pre-construction phase the design of the construction site and the planning and scheduling of activities site project and planning activity. The subsequent sections serve as an introduction to the key themes and topics that will be further explored in Section 5 of this thesis. Section [4.1] discusses the preliminary considerations for the setup of the 4D BIM project, laying the groundwork for detailed analysis in later chapters. Section [4.2] introduces the application of Agent-Based Simulation for risk analysis, with a focus on how it models site activities and the associated intrinsic risks. Finally, Section [4.3] outlines the approach to risk treatment and decision support, emphasizing how predictive data can enhance safety management strategies in construction projects.

4.1 Modulo 1: 4D BIM planning

This module marks the initial phase of the framework. Here, the safety manager, with the collaboration and coordination of site technicians from the client and various involved companies, formulates an initial hypothesis of the construction sequence and a detailed program of work activities. The site design choices made during the pre-construction phase are fundamental and lay the foundation for:

- **Spatial planning of the site**: determining space allocation for various construction, storage, and movement activities.
- **Resource allocation:** identifying and scheduling machinery, equipment, and human resources to avoid conflicts and ensure smooth progress.
- **Safety measures:** implementing collective safety measures that protect workers and equipment throughout the construction process.

Project and plans are elaborated with a 4D BIM-based methodology. Thus, we possess the project model and construction site, aligned with the predetermined timeline of activities and its resources. In this module, we emphasize the integration of the 4D BIM data into advanced 3D development and simulation platforms for translation into an Advanced Agent-Based Simulation Model for risk analysis and site planning. In Section [5.1], after an initial analysis of the practices and good logic of setting up a 4D BIM model, the main aspects of data acquisition will be analyzed, summarized in the following points:

- **Entity classification:** Identification and organization of geometric and informational data necessary for fully managing the model for the uses indicated in the subsequent point. Correct structuring of the dataset is crucial for the accurate and efficient use of the model during later design stages.
- **Structuring and Use of BIM datasets:** Specific function and use of different datasets for creating the simulation environment and for managing the simulation itself. Different datasets serve specific purposes in the simulation and project management context. Understanding and effectively using these datasets can significantly enhance the precision and utility of the simulation environment.
- **Data exchange format:** The methods by which data are exchanged between different systems are discussed, as ensuring compatibility across platforms is essential for facilitating interoperability. The importance of a common, open, and standardized language is crucial for maintaining the integrity and usefulness of 4D BIM data within the advanced 3D simulation environment.

This sets the stage to perform an Advanced Agent-Based Simulation System for risk estimation and site planning. The configuration of models and their corresponding datasets during the 4D BIM modeling phase allows their use for translating specific design specifications of the construction site, planning, and scheduling of activities, into virtual three-dimensional simulation scenarios corresponding to specific temporal periods of the planned construction process.

4.2 Modulo 2: Advanced Agent-Based Model and Simulation

Once the project for the construction of the work has been defined, the potential risks associated with site organization and activities are identified. In accordance with ISO standards, the risk analysis phase follows, during which safety and site managers calculate activity risk values by estimating 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. The manager is supported by methods and systems for risk estimation and decision-making that, however, are not able to evaluate the effectiveness of these choices. At this point, the Advanced Agent-Based Simulation System for risk estimation comes into play by supporting the safety manager in estimating the likelihood of occurrence of hazardous events (H) and in the calculation about the Vulnerability (V) and Exposure (E) of those events. Performing the simulation of planned activities within the BIM model using autonomous agents allows monitoring of the interactions and dynamics that occur among the agents in that specific work environment. The collection of these data in real-time allows the analysis of emerging behaviors that could develop within a specific construction site, highlighting inefficiencies in design and planning, even those that might increase the risk levels of a work activity.

This module, the core of the system, will address all stages of setting and performing the three-dimensional Agent-Based model simulation of site activities, integrating project and planning BIM data. In Section [5.2], after an overview of the characteristics of existing advanced 3D modeling and simulation tools, the following three layers according to which it is organized will be addressed:

- **Data integration:** having the data organized according to the specific uses defined in Module 1, this layer will analyze the ways of creating the actual Agent-Based Model. After a useful deep dive into the classification of entities operating on-site, this layer will address the main aspects and issues related to the generation and characterization of entities in the advanced simulation environment in relation to their functions, for example, for creating the context of the simulation, the agents of the model, and the hazards and/or dangerous events.
- **Data Process:** having created the context of the simulation and having the resources of the site and data of the planning of the activities at hand, this layer will address the aspects related to the simulation of the agent model. The steps will be explained through which, by exploiting the interconnection between the scheduling data and the entities of the site integrated into the system, it is possible to set up construction site scenarios corresponding to specific moments of the construction of the work, populate them with agents corresponding to the resources in play at that specific moment, and start simulations in which the agents operate in the context of the three-dimensional simulation. In relation to our characterization of the hazard and dangerous event in this specific system (Data integration Layer), the layer will address the aspect of recording and collecting data of interest from the simulation.

- **Data Visualization:** this layer will illustrate how data from the simulation can be processed and visualized in a form that is readable and useful to the safety manager. By exploiting aggregation techniques and interpolation of the data collected during the simulation, derived from the different resources and entities operating during the simulation, it is possible to obtain significant information directly in the three-dimensional environment. It will be illustrated how a heatmap representation on the three-dimensional model of the events of interest provides an intuitive representation of the results and allows for quick identification of the emerging critical aspects related to the project of construction site setup and planning of activities.

4.3 Modulo 3: Risk treatment and decision support

This module focuses on the culminating phase of the framework, dedicated to risk treatment and the enhancement of decision-making processes through the application of predictive data generated by the Agent-Based Simulations of construction site activities. The primary objective of this module is to utilize the analytical capabilities provided by advanced simulation outputs to inform and refine risk management strategies. The central aim of Module 3 is to transform the raw data and analysis provided by the simulations into actionable insights that can be applied directly to construction site planning and risk mitigation strategies. This involves interpreting the simulation-generated heatmaps and statistical data to understand potential risk hotspots and the effectiveness of proposed safety measures. The module enables an iterative process where the results from simulated scenarios help to improve construction site plans and enhance worker safety protocols.

5 Top level architecture of the Advanced ABMS System for site activity risk assessment

The high-level architecture of the proposed methodology is presented in Figure 8, illustrating the functioning, relationships, and dependencies between BIM-based 4D design, planning activities, the Advanced Agent-Based Simulation System for construction site operations, and the Risk Assessment phase.

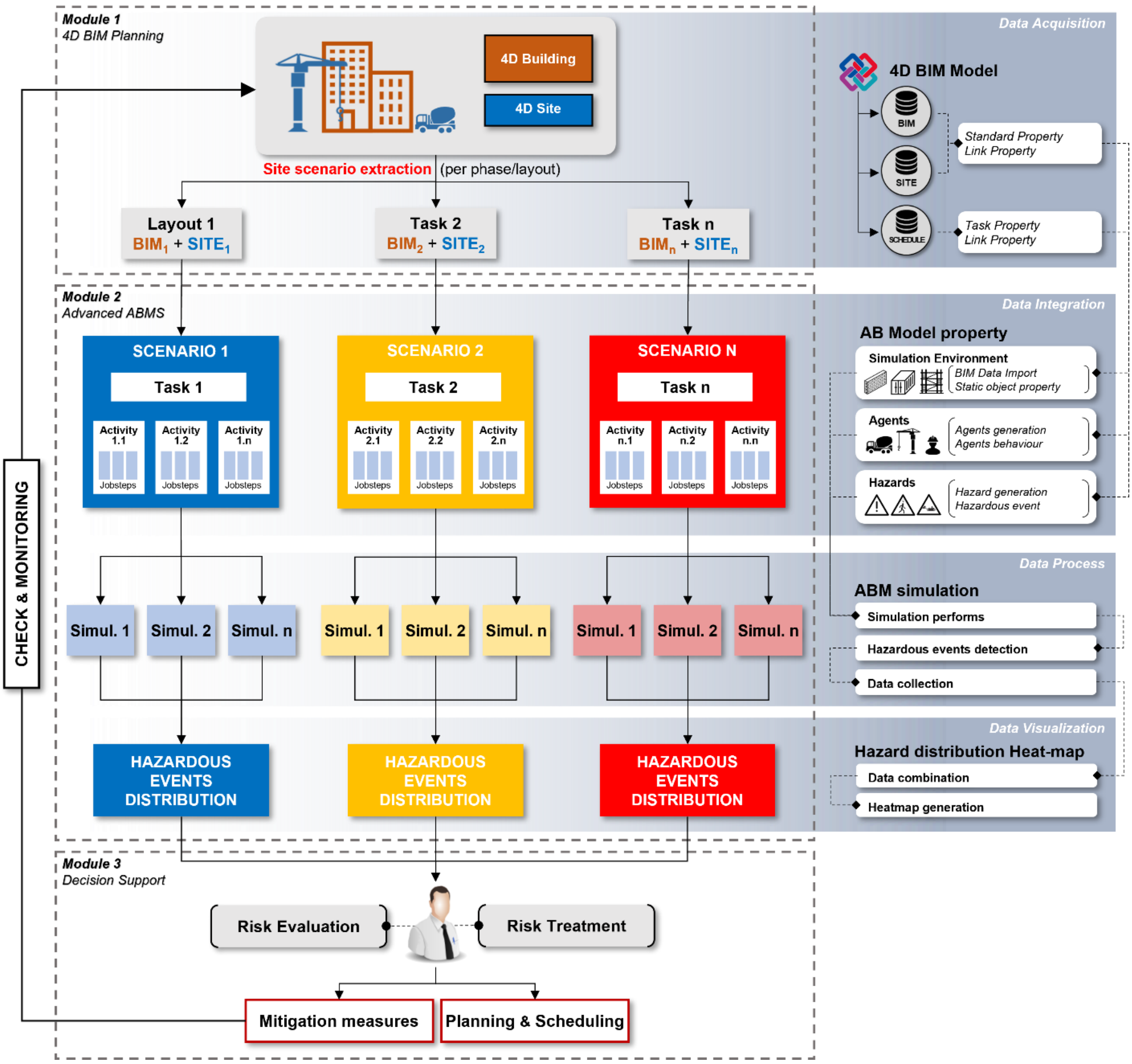


Figure 8 – Framework Architecture of the Advanced BIM Agent Based Simulation System for risk analysis of site activities

Figure 8 offers an integrated view of the system, showcasing the progression from data acquisition to hazard visualization and monitoring. The process begins with collecting and integrating BIM data, which provides a detailed representation of the construction site layout and planned activities. Subsequently, the system performs Agent-Based Simulations across different operational scenarios, where agents, representing workers and machinery, interact within the environment, enabling the detection of potential hazardous events. The simulation results are then visualized through a risk heatmap to highlight critical areas, supporting informed decision-making for safety management.

Following this initial overview of the system framework, the subsequent sections will examine each component of its architecture in detail. Each module of the framework (Section [4]) will be thoroughly analyzed, outlining the specific steps within the identified process layers that are essential for the effective implementation of this system, including data acquisition and integration, hazard detection through simulation, risk distribution visualization, and the monitoring phase in the context of construction safety planning and management.

5.1 Module 1: 4D BIM Planning: Model set up for advances ABS of site activities

Module 1 consists of a single Data Acquisition Layer, where the rules and tools for exchanging information between the BIM model and the simulation environment are established. This represents the initial phase of the process, where, through the analysis of a real construction site environment, a method for the classification, implementation, and exchange of information from the project and construction BIM models is defined.

5.1.1 Data Acquisition Layer

The required BIM data (Figure 3), organized according to specific format standards, are retrieved from the 4D BIM models of both the project and the construction site to feed the virtual construction scenarios in the advanced simulation environment. The process was divided into three key steps:

- **Classification and grouping of construction site components** based on their functions and characteristics as site entities (Section 5.1.1.1), both in the real-world environment and in the simulated scenario;
- **Identification and primary implementation of the datasets** required for managing the different classes of site entities within the advanced simulation environment (Section [5.1.1.2];
- **Definition of a data exchange format**, following the selection of the advanced development platforms and considering that the system developed in this research operates within a BIM process (Section [5.1.1.3]).

In the following sections, each of these steps will be discussed in detail, with the aim of providing a scalable and repeatable method for data exchange between BIM software and advanced 3D modeling and simulation systems. This method is intended for use in Agent-Based Simulations of construction site activities.

5.1.1.1 Site entity classification

In the context of a construction site, complexity arises not only from project development and interactions with the environment but also from the segmentation of the construction process into multiple tasks and subtasks, often performed in parallel, involving various resources (materials, equipment, labor, machines). The interactions between these entities, influenced by multiple conditions affecting the construction environment, workers, machines, and equipment (Section [3.2]), can lead to hazardous events, thereby posing safety risks for workers (Figure 9).

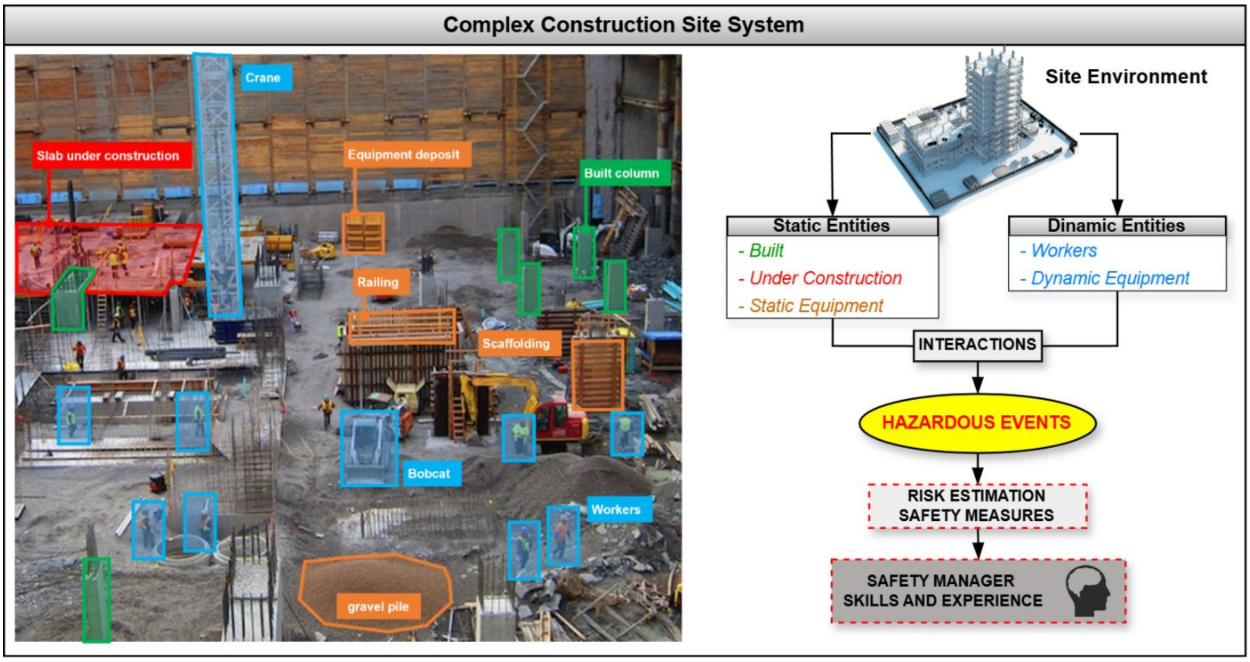


Figure 9 - Analysis of the key entities within the complex construction site system

In the construction process, the need to create a component initiates a task that requires a series of activities to be completed. Depending on the chosen construction method, these activities are structured into a sequence of job steps. Each job step, representing the specific work to be carried out on-site, demands the utilization of essential site resources such as materials, equipment, and worker, which are critical for executing the planned operations (S. Zhang et al., 2014).

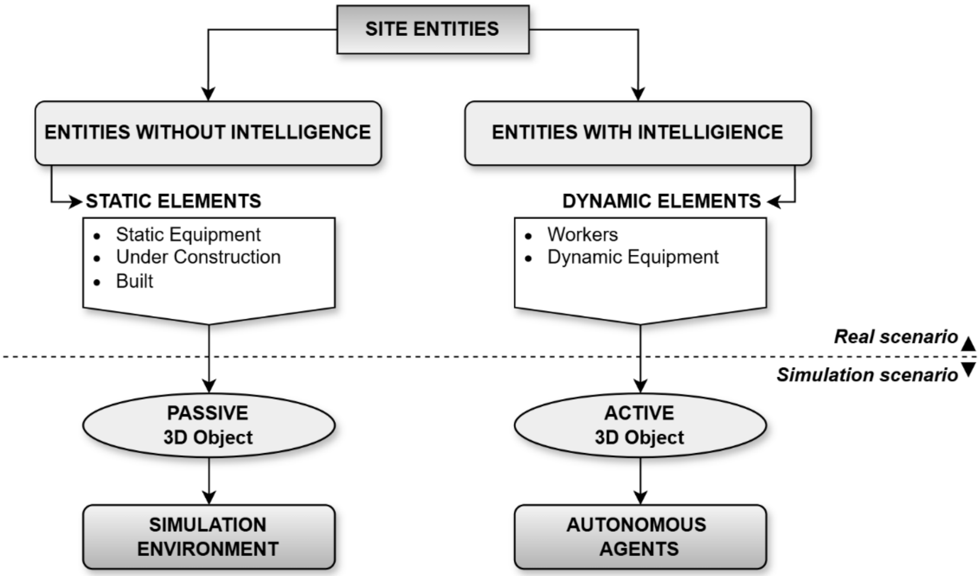


Figure 10 - Site entities classification for Advanced ABMS of site activities

In a 4D BIM model, resources such as materials and equipment are represented as parametric 3D digital components within either the project model (built elements, under-construction elements) or the construction site model (static equipment, though not always machines). Meanwhile, resources like workers and machinery are represented as properties of individual activities within the construction activity schedule. Both categories of data are necessary for implementing the simulation model. The classification presented allows for the identification of two primary groups of components corresponding to the two stages of development in the Agent-Based Simulation model:

- **Static Objects**: These are static 3D BIM digital components that represent the environment/context within the simulation model (Section [5.2.1.1]). These components are included in the form of 3D BIM objects in the original models. This requires the development of a method for managing both the geometric content of the 3D BIM component, essential for constructing the physical-digital 3D environment, and the 4D BIM informational content linked to the component, which is crucial for transferring scheduling information for managing the 3D BIM components in the simulation scenario. It is also necessary for implementing site resources classified as dynamic objects, as detailed below.
- **Dynamic Objects**: These are dynamic digital components representing autonomous agents within the simulation model (Section [5.2.1.2]). These components are generally not modeled and exist as informational content/properties linked to the 3D BIM component's activity. As dynamic entities, such as workers or machinery, must act autonomously on-site in relation to the tasks to be performed, once the implementation mode is defined in the form of a 3D digital object using the scheduling information, the focus shifts to their behavior. This involves researching and developing a method to implement an AI-driven autonomous decision-making system to enable independent operation within the simulation of construction activities. The entities involved in the construction site, classified as key actors, are organized based on their role and interaction in the construction process as follows.

<table>
<tr><th colspan="5">ENTITIES WITHOUT INTELLIGENCE</th></tr>
<tr><td colspan="5">Static elements, which constitute a fixed or temporary obstacle in the construction space and play a passive role in the construction activity</td></tr>
<tr><th colspan="2">Real Site Scenario</th><th>4D BIM</th><th colspan="2">Virtual Scenario</th></tr>
<tr><td>Built elements</td><td>have been object of construction activities in previous phase, that occupancy permanently space on site.</td><td>3D Component</td><td rowspan="3">Static Element Passive 3D Object</td><td rowspan="3">3D Simulation environment</td></tr>
<tr><td>Under construction elements</td><td>they are the subject of ongoing construction activities, determining the permanent and increasing occupation of a certain space necessary for its construction.</td><td>3D Component</td></tr>
<tr><td>Static equipment</td><td>installed or stored during the phase, they can change position/configuration only if moved or handled.</td><td>3D Component</td></tr>
</table>

Table 4 – Site entities classification for Advanced ABMS of site activities: Static elements

ENTITIES WITH INTELLIGENCE				
Dynamic elements, which contribute to the performance of the work activity possibly also using static entities.				
Real Site Scenario		**4D BIM**	**Virtual Scenario**	
Workers	*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.*	*Task Property*	*Dynamic Element Active 3D Object*	*3D Autonomous Agents*
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.).*	*Task Property*		

Table 5 - Site entities classification for Advanced ABMS of site activities: Dynamic elements

This classification provides a structured and grouped understanding of site entities, which is essential for transferring their characteristics into the virtual simulation environment.

5.1.1.2 Dataset for uses of site entities for Advanced ABMS of site activities

The characteristics and types of some entities included in the newly defined classes are identified during the planning and scheduling phases of each job step. In a 4D BIM-based process, these entities must be represented within the federated project model in a specific form. The starting point for this process is a federated 4D BIM model that coordinates all disciplines involved, organized according to standard methods for 4D BIM implementation. Each entity, whether physically modeled or represented by its associated data, is organized according to the relevant tasks, activities, and job steps defined in the project's work schedule. This organization is achieved through parameters, datasets, or properties that facilitate the temporal sequencing of elements according to the construction process model. This organization of data follows the same logic used in 4D BIM processes, where data and links between different datasets are systematically structured. This approach is directly applied to the proposed system for use of BIM models in advanced Agent-Based Simulations, ensuring consistency between the two systems. By replicating the 4D BIM structure, it enables the seamless generation of three-dimensional simulation scenarios (representing both the site environment and agents) and the integration of relevant data into the simulation. The essential datasets required for building and organizing the simulation model in alignment with the project schedule have been identified and grouped into the following three macro-categories (Figure 11):

1. **Identity Properties:** To begin the implementation phase, properties such as Category, Type, and Identification data are integrated into the 3D BIM model. These properties ensure a structured breakdown of the project by clearly defining the BIM model's entities in relation to work activities.

2. **Link Properties:** Each component must be classified with parameters that enable the connection between the 3D model's data and the scheduling information related to site activities. Properties such as Creation/Demolition phase are used to contextualize each component within the correct site configuration and serve as filters to align the model with the appropriate simulation scenario. Additionally, properties such as *"Task ID", "Activity ID", and "Job Step ID"*, commonly used to increase the level of scheduling detail, facilitate the management of various site and project components within each simulation scenario and their connection to the corresponding task properties, both in the 4D BIM model and in the simulation model.
3. **Task Properties:** As previously mentioned, identification and linking parameters provide the mechanism for transferring scheduling information to the simulation. These properties enable the generation and management of 3D model components during the simulation of activities, in accordance with the project schedule.

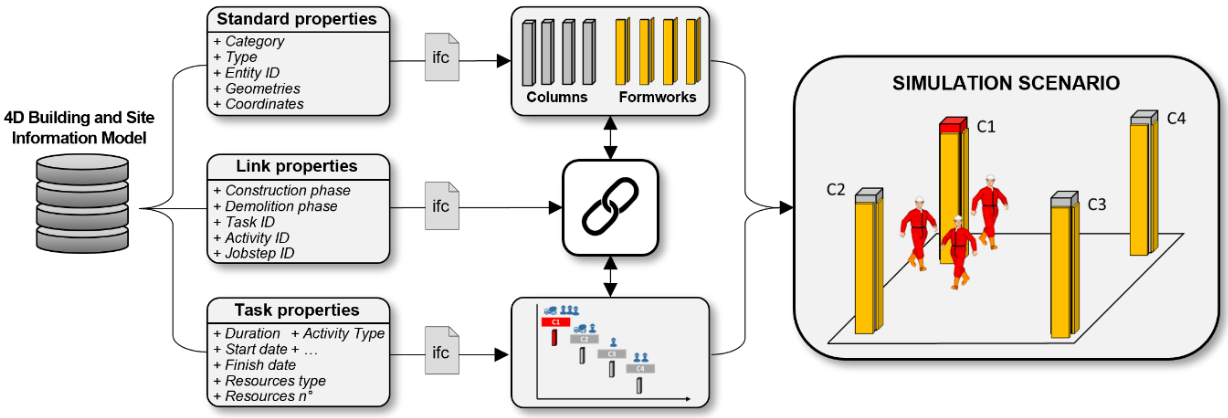


Figure 11 - Dataset for uses of site entities in Advanced BIM Agent Based Simulation System

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

5.1.1.3 Data format exchange

This module aims to enable the advanced simulation system for construction activities to read and utilize the identified datasets from the 4D BIM model, and to establish a data exchange system that facilitates the implementation and use of the simulation system within any construction planning and risk analysis process. Currently, BIM software and advanced construction management tools with integrated 4D BIM modeling functionalities use proprietary systems for the exchange of geometric and informational models. This facilitates the connection of parts only when both specific software packages are available. Similar issues are encountered between advanced modeling/simulation tools and BIM software.

In this context, the open standard for data representation and exchange in the BIM domain, developed by *Building SMART*, known as Industry Foundation Classes (IFC), is highly beneficial. IFC is designed to facilitate interoperability between different software applications used in the construction industry, allowing for the sharing and integration of information among various stakeholders. The latest versions of the IFC format have a structure capable of representing both the geometric and informational content of the project, site, and construction management. This allows for managing the information and data identified in the previous datasets, enabling a classification of the three groups of model properties according to IFC schema/structure. While it has been established that the IFC structure is adequate for transferring the input data necessary for the simulation of activities, a system ready to receive such a format will be required, as described in the following section.

5.2 Module 2: Advanced Agent Based Model and Simulation

Agent-based modeling and simulation (ABMS) is a computational approach used to model complex systems consisting of autonomous and interacting agents (MacAl & North, 2010). Agents possess a form of intelligence, defined by behavioral rules that allow them to interact with both their environment and other agents. The core of the agent-based approach lies in the autonomy of these agents, achieved through a set of behavioral rules enabling them to analyze the environment in which they operate, make decisions, and perform actions within a continuous perception-decision-action cycle. Typically, the environment itself is passive, and the emergent phenomena arise from the combination, interaction, and interference between agents (Simeone et al., 2017b).

In this study, the agent-based approach is employed to model a construction site system during the execution of scheduled activities. Various types of agents are used to simulate work tasks and navigate the site environment based on predefined behavioral rules, interacting both with the environment and with each other. The primary goal is to record and map the interactions between agents that occur during the simulation, having predetermined which interactions correspond to hazardous events. This enables the identification, classification, and localization of potential safety hazards within the construction site. The data generated through this process provides essential support for safety managers, helping them to identify preventive measures related to site layout and activity planning, ultimately enabling the testing and validation of the construction site's safety plans and activity schedules.

A typical agent-based model is characterized by three fundamental elements: 1) **simulation environment**, 2) **autonomous agents**, and 3) **simulation rules** that govern agent behavior and the simulation process. This section will explore in detail the key aspects related to the implementation of these fundamental elements, starting from a 4D BIM model. Additionally, it will cover the final stages of result processing and visualization, which are crucial for evaluating the simulation outcomes

The implementation and development of the agent-based model and its corresponding simulation will be shaped by the characteristics of the platform chosen to support the advanced simulation system. Numerous specialized platforms for ABMS exist, most of which facilitate the development of two-dimensional models, while a few have integrated 3D capabilities. However, this research aims to leverage more innovative and high-performance tools designed for the development of 3D digital content not necessarily created specifically for ABMS, but rather for advanced three-dimensional environments such as game engines. Examples of such tools include:

- ***Unity 3D***, developed by *Unity Technologies*, is recognized for its accessibility and versatility. It supports a wide range of devices and offers an intuitive development environment. Furthermore, *Unity* integrates the *"NVIDIA PhysX engine"*, enabling realistic simulations of rigid body dynamics, fluid dynamics, and cloth simulation.
- ***Unreal Engine***, developed by *Epic Games*, is renowned for its photorealistic rendering capabilities and the power of its `Blueprint scripting language`, in addition to support for `C++`. It also includes the *"Chaos physics engine"*, which facilitates advanced simulations involving destruction, deformation, and particle dynamics.
- ***NVIDIA Omniverse*** stands out as a real-time collaborative platform that integrates advanced physical simulation tools and high-fidelity rendering, leveraging the computational power of *NVIDIA GPUs*. *Omniverse* uses *"PhysX technology"* to provide detailed and accurate physical simulations, making it a highly performant tool for interactive and immersive experiences.

These platforms are advanced software environments for the development of 3D content, simulations, and visualizations, tailored to meet the needs of creators and developers across various sectors. They offer powerful real-time physics and rendering engines, comprehensive scripting and programming capabilities, and broad compatibility with different platforms and formats. For the purposes of this research, selecting such platforms to develop an Advanced Agent-Based Simulation System for construction site activities based on data derived from a 4D BIM model offers several key advantages:

- **High-performance rendering engines** that enable the visualization of 4D BIM data with a high degree of realism and interactivity. This is essential for understanding and communicating complex site dynamics more effectively.
- **Integrated physics engines**, such as *"PhysX technology"* in *Unity* and *Omniverse*, or *"Chaos physics engine"* in *Unreal Engine*, which provide realistic simulations of rigid body dynamics, fluid interactions, and agent behavior. This improves the precision and reliability of Agent-Based Simulations within the construction context.
- **Compatibility with various tools and data formats**, including 4D models formats generated from Building Information Modeling (BIM) software. This allows for the seamless import and real-time updating of site data within the simulation environment.
- **Real-time collaborative capabilities**, particularly with platforms like *NVIDIA Omniverse*, which enable multidisciplinary teams to work together on the same project, facilitating communication and coordination between different stakeholders involved in the construction process.
- **Advanced scripting languages** (e.g., `C#` in *Unity*, `Blueprint` and `C++` in *Unreal Engine*, `Python` in *Omniverse*) that allow for the customization of simulations to address specific project requirements. This enables the creation of complex agent behaviors tailored to construction activities.
- **Powerful visualization and analysis functionalities**, which facilitate real-time monitoring of construction operations, allowing for the identification of potential issues and optimizing processes as needed.

Having identified the fundamental aspects of these platforms, which generally operate in similar ways, we can now proceed to a detailed analysis of the system's core functionalities. This will focus on the implementation and operation of the proposed Agent-Based Simulation system across the following layers: 1) the **Data Integration Layer** (Section [5.2.1]), which deals with the classification of site entities into static and dynamic groups, defining the rules for their implementation and behavior within the simulation; 2) the **Data Process Layer** (Section [5.2.2]) which manages the execution of the simulation and the processing of data necessary for risk analysis, including Hazard, Vulnerability, and Exposure components; and 3) the **Data Visualization Layer** (Section [5.2.3]), which will display the results in a comprehensible format, such as heatmaps, to highlight hazard distribution and provide actionable insights for risk mitigation.

5.2.1 Data Integration Layer

The system builds upon the classification of site entities as outlined in Section [5.1.1.1]. This classification divides entities into two macro-categories—static and dynamic—each requiring a distinct configuration within the simulation model, based on their characteristics and roles in the real construction site system. Following the identification of these two major categories, this layer is responsible for:

1. Evaluating the steps necessary for integrating these entities into the system, using both the geometric and informational content provided by BIM (Section [5.2.1.1]);
2. Defining a method for implementing a decision-making system, along with the rules and properties needed to model the behavior of agents to performs Advanced Agent-Based Simulation of site activities, using Advanced Modeling and Simulation Platforms (Section [5.2.1.2]);
3. Developing a method for modeling risk and hazardous situations within the Advanced Agent-Based Simulation Model, aimed at recording simulation data on such events for subsequent analysis (Section [5.2.1.3]).

Through this approach, static entities, such as equipment and built elements, will be configured with their physical and temporal properties to ensure accurate integration into the simulation environment. Dynamic entities, such as workers and machinery, will be modeled as autonomous agents with predefined behaviors, enabling them to interact with both the environment and each other. Moreover, safety-related conditions, such as equipment positioning and potential collisions, will be systematically simulated to identify, assess, and mitigate risks.

5.2.1.1- Virtual environments rules

The simulation environment, designed to replicate a real construction site, incorporates “Static entities” (Table 5) that represent fixed or temporary equipment and obstacles within the construction space. These static entities play a passive role in the construction process and include contextual elements, completed or under-construction structures, static equipment, site zones, and more. Understanding and integrating these static entities within the simulation system framework is critical for creating a realistic and functional virtual construction site. In a Building Information Modeling (BIM) context, static entities are not merely geometric representations but serve as essential components for transferring information. Beyond the “*Identity Properties”* that identify the entities and the *“Task Properties”* that align them with the project schedule, the term *"Link Property"* refers to the metadata associated with these entities. This metadata connects them to the planning data embedded within the *"Task Properties"*. Integrating these static entities from the 4D BIM model into the Advanced Simulation System is essential, as it enables the simulation to accurately mirror the spatial and temporal evolution of the construction site. This integration allows the virtual environment to reflect the planned construction activities, site layout, and scheduling stages during activity simulation.

This section outlines the process of integrating static entities from BIM models into an advanced virtual simulation platform, focusing on both data importation and the assignment of object properties. The *Data Import and Conversion* process enables the transfer of both geometric and informational content from the BIM model into the simulation environment. The subsequent step, assignment of *Static Object Simulation Properties*, involves defining the physical attributes that allow for realistic interactions within the simulation, facilitated by the Advanced Modeling and Simulation Platform. These two stages are crucial for ensuring a seamless and accurate representation of the static elements of the construction site within the virtual environment:

1. **Data Import and Conversion**: Sorbi et al., 2022, have developed a robust method for transferring both the geometric and informational content of static entities from the BIM model in *Unity Platform*. This method involves preprocessing the IFC file using the *IfcConverter* utility provided by the open-source *IfcOpenShell* library. The process involves:
    - **Geometry Import**: The geometric data of model entities is converted into the *.obj* format. This format is widely supported and optimizes the representation of 3D shapes within the simulation environment.
    - **Data Import**: The associated metadata for each entity is imported in *.xml* format. It is chosen for its flexibility and ability to represent complex hierarchical data structures. However, this method requires an additional development step within the simulation platform, specifically necessitating a system capable of reconstructing the model hierarchy and the associated data, then correctly linking them to the appropriate model entities. This further complicates the development process and may lead to data loss or improper data distribution within the components. Consequently, during the implementation phase of the system's test model, alternative solutions for importing the IFC model into the chosen development platform were explored and considered.
2. **Static Object Simulation Properties**: Once imported, each BIM object's content must be converted into 3D object in the advanced simulation environment. These 3D objects are then categorized and endowed with properties that define their characteristics and behavior within the simulation environment. Advanced simulation tools and game engines platform facilitate the assignment of physical properties such as:
    - **Gravity**: Simulating realistic gravitational forces on objects.
    - **Mass**: Assigning appropriate mass values to objects to influence their interaction dynamics.
    - **Friction**: Defining frictional properties to simulate realistic movement and interaction between surfaces.
    - **Navigation property:** Properties to be assigned to the walkable surfaces of the simulation model, highlighted in blue in Figure 12, define areas navigable by agents, facilitating movement and

access to action targets. These surfaces ensure that agents can traverse the construction site efficiently, simulating real-world navigation and moving between predefined action targets based on the actions that autonomous agents have decided to perform.

These properties enable the simulation of realistic behaviors and interactions, allowing agents (both workers and human-operated machines) to interact with static entities as they would in a real construction site.

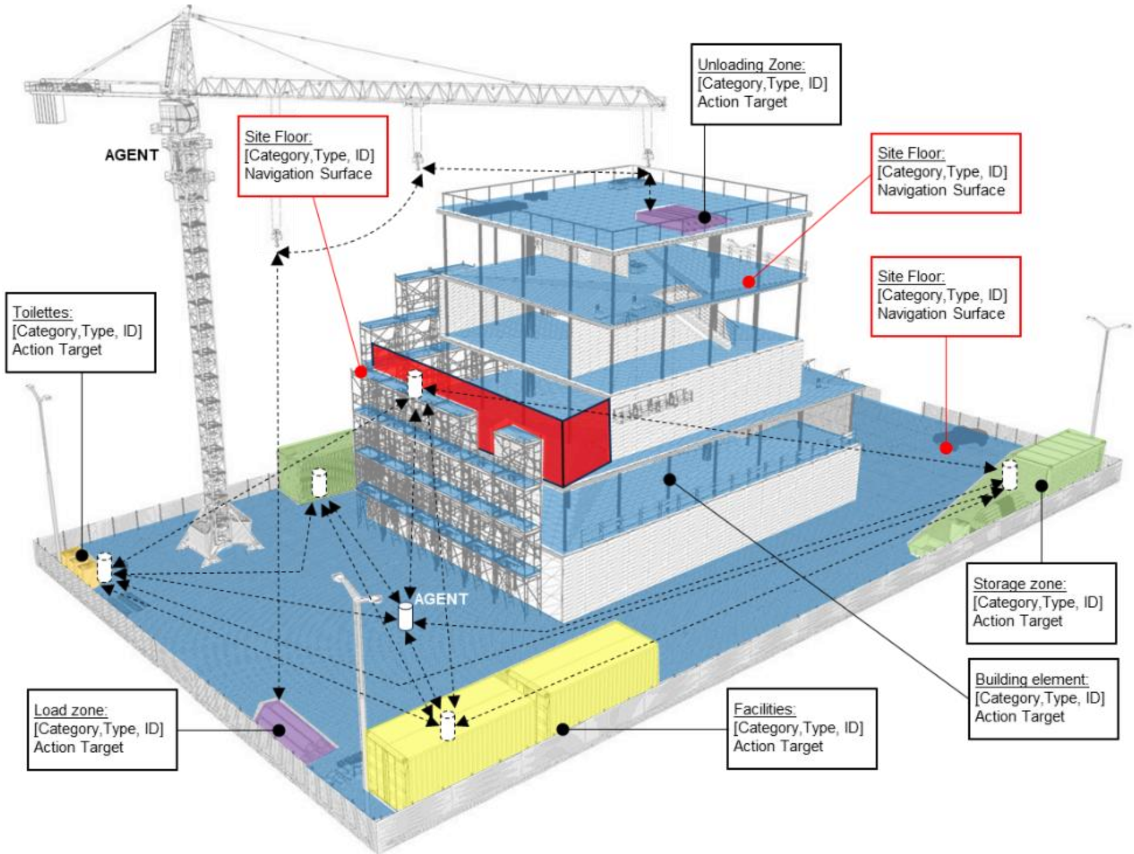


Figure 12 – Example of Virtual site environment of advanced simulation model for site activity risk assessment

The integration of static entities into the simulation environment is streamlined by automating the process of characterizing these entities. Access to BIM data and the definition of logics and rules for property implementation are crucial steps. Once these logics and rules are established, scripts can automate the association and data reconnection processes. These scripts utilize BIM component properties (*Standard, Link, and Task properties*) to ensure seamless integration. This automation not only enhances efficiency but also ensures consistency and accuracy in the representation of static entities within the simulation.

In summary, the effective incorporation of static entities from BIM models into a simulation environment requires a meticulous approach to data importation, conversion, and property assignment. By leveraging advanced tools and automation scripts, it is possible to create a highly realistic and functional virtual construction site that accurately mirrors the planned evolution of real-world construction activities. This process not only enhances the simulation's fidelity but also provides invaluable insights into construction planning and execution.

5.2.1.2- Autonomous agents rules

In the context of construction site simulation, agents represent dynamic entities that are either equipped with intelligence or require intelligent control to move and operate within the site. These dynamic entities play an active role in work activities and may interact with static entities within the construction site environment. As previously discussed, examples include site workers and dynamic equipment that move between different areas of the site to perform tasks, such as transporting materials, storing and retrieving supplies, or accessing facilities like toilets or logistical stations.

The 4D BIM model serves as a critical 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 links resources to specific activities outlined in the project schedule. These resources, whether modeled or not, are characterized by properties such as identification, typology, dimensions, and cost, all of which are contained within the *Ifc* file of the 4D model. These entities are utilized in various aspects of the 4D programming process: to plan their deployment, verify their positioning and sizing on-site, schedule the duration of activities, and assess the financial impact (e.g., cash flow) within the construction project.

In this study, dynamic site resources, such as machines and workers, are proposed as *AI autonomous agents* within the advanced BIM Agent-Based Modeling and Simulation (ABMS) System for site activities. This system focuses on risk estimation, site management, and activity planning. The innovative aspect of this approach lies in the representation of construction site resources, not only as data linked to specific activities but as *dynamic agents* within the system, possessing their own behavioral components. These behaviors are directly tied to the actions they perform within the simulation. This represents a progressive advancement compared to traditional 4D simulations, even those that are highly sophisticated.

To achieve this, the process of generating and representing these agents as *3D Dynamic objects* within the simulation environment, derived from project BIM data, was first analyzed. Following this, the critical and complex task of implementing agent behavior was thoroughly investigated and is further elaborated upon in the following sections.

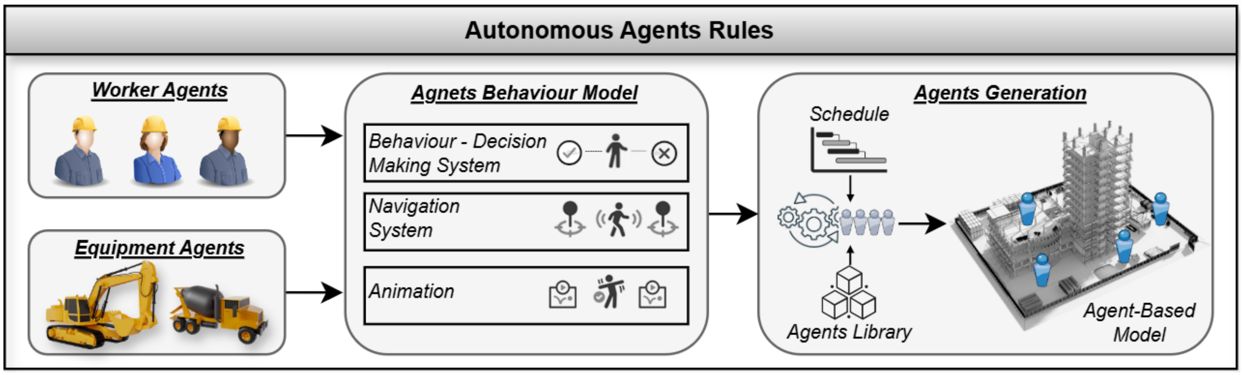


Figure 13 - Model for generating and managing autonomous agents (workers and equipment) to simulate site activities and interactions based on 4D BIM data

Agents generation

The process begins with the generation of the 3D model, where each BIM component corresponds to static entities or 3D Objects within the advanced simulation environment. These 3D Static Objects are associated with 4D BIM data structures or external components containing task information, referred to as *"Task Properties"* in this context. As previously indicated, this data is directly linked to the Game-Objects through scripts and stored in external databases, accessible via formats such as Ifc files or exported schedules file.

By employing scripting or programming logic within the advanced simulation platform, the resource data associated with each 3D Static Object in the site environment can be automatically accessed and interpreted. This enables the system to determine the characteristics and properties of the dynamic agents (representing workers or machines) that are to be instantiated within the simulation scenario. This *"Resources data"* includes attributes such as the *number of agents*, their *types, skills*, and the actions they perform, as well as additional properties derived from the referenced components, such as the *location* of static objects or action targets, and the associated task details (e.g., *"task ID", "Duration", "Start and end dates"*). Using this data, along with an *"Automatic instantiation function"* based on the 4D BIM data in *Ifc* format, proposed below and developed in Section [6.2.3.2], and utilizing a *"Library"* of compatible 3D agents for the simulation platform (with varying levels of performance), site entities representing workers and machines are dynamically created and instantiated within the simulation scenario. This automated process ensures the seamless integration of task information from the 4D BIM model into the simulation, allowing for the real-time generation and management of dynamic agents that reflect the planned construction activities. Following the proposed process below, it is possible to instantiate and instruct 3D agents within the simulation model based on the activity schedule. These agents can then be managed within the simulation by another function dedicated to orchestrating the simulation over time according to the project schedule, activating and visualizing both agents and 3D Static Objects within the simulation.

The proposed process for instantiating dynamic construction site resources as autonomous agents in an advanced construction activity simulation model is divided into three main steps:

1. **Check Scenario**: The script analyzes the task data of all game-objects in the scene to detect static entities relevant to the task.
2. **Access Library**: Task properties provide the necessary information to access a library of pre-processed 3D models representing construction site resources.
3. **Select and Position Model**: Prefabricated 3D models are selected to represent each type of dynamic agent and are positioned at specific locations in the scene according to the construction components.

In the simulation model, the agent instantiation process executed by the advanced simulation platform script begins with analyzing the task data of all game-objects in the scene to identify relevant static entities. Subsequently, reading the task properties provides access to a library of pre-processed 3D models of construction resources. This enables the appropriate selection of models to represent dynamic agents, which are then placed at specified positions corresponding to the construction components (Figure 13). 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 better described in the following section.

Agents behavior

The second aspect, the heart of Agent-Based Simulation and the autonomous agents themselves, is the behavior of this virtual entity. This behavior in the agent-based model translates both into a decision-making system that allows both the choice of how to act in the simulation environment, and the performance of the action itself and the response of the agent in carrying out this action. 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 for example 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 can talk about *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. The question therefore lies in evaluating and identifying methods for the development of behavior for *AI Agents*, which can model a behavior congruent with that manifested on the construction site by workers and machines in relation to the work activity to be performed and the configuration of the construction site in that scenario.

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:

- **Movement and Navigation:** Agents must efficiently move from one location to another within the virtual construction site, navigating obstacles and adhering to spatial constraints. Pathfinding algorithms and movement functions within game engines can be employed to calculate optimal paths, considering factors such as terrain topology and dynamic obstacles.
- **Lifelike Animations:** 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.
- **Decision-Making System:** 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 System"* approaches 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, as developed for the test model in Section [6.2.3.2].

Behavior model

The modeling of autonomous agent behavior is a very complex aspect, in particular human behavior, which is still the subject of many studies today. To date, various models of autonomous agents have been developed for the effective representation of human behavior. Depending on the level of complexity of the behavior and the specific characteristics to be simulated, the most common and powerful models of representation of human behavior are the following:

- **Reactive Agents:** These are the simplest types of autonomous agents. They do not possess a historical memory of their previous actions and respond directly to stimuli from their surroundings. Their decisions are based on predefined rules or if-then conditions. These agents are useful in scenarios where rapid responses to specific stimuli are essential. Reactive agents can be useful for modeling specific and simple aspects of human behavior, but they are generally not suitable for capturing the full complexity of human behavior
- **Deliberative Agents:** An agent with a behavior model for planning actions based on the internal state of the model. These agents make rational and complex decisions by following a goal planning process in relation to changes in the model's surroundings. It is therefore configured as a model suitable for simulating various human behaviors, including the execution of tasks.
- **Emotional Agents:** Emotional agents are designed to simulate human emotions and use these emotions to influence the agents' decisions and actions. Emotions can affect agents' perception, attention, memory, and decision-making, making their behavior more realistic and human. It is a model suitable for simulating human behavior and decision-making influenced by perception, attention, memory, etc.
- **Learning Agents:** Learning agents improve their behavior through experience, using machine learning techniques such as reinforcement learning. These agents tend to optimize their decision-making and actions based on rewards and penalties received from the system. These agents are ideal for simulating human behavior in environments where continuous improvement and adaptation is required, such as in training scenarios and operational simulations.

To represent human behavior in an Agent-Based Simulation system, deliberative, hybrid, emotional, and learning agent models provide the capabilities needed to simulate complex decisions, emotional reactions, social interactions, and experience-based enhancements. The choice of model depends on the level of detail and realism required in the simulation. A hybrid model that combines these aspects best represents human behavior, as it integrates the strengths of each approach. Deliberative agents manage long-term planning, reactive agents respond to immediate stimuli, emotional agents simulate emotional reactions, and learning agents learn and adapt over time. By combining these elements, you get a more realistic and comprehensive simulation of human behavior.

Behavior model implementation for site autonomous agents

Sorbi et al., 2022 demonstrates the implementation of a simplified behavior model through the incorporation of a decision-making system in agents, specifically for selecting movement actions within a 3D simulation scenario, without considering animations, emotional states, or learning aspects. The authors propose the implementation of *Deliberative agents* for Agent-Based Simulation of construction site activities, suggesting the development of a *BDI (Belief-Desire-Intention)* architecture that utilizes a utility-based action planning system to define agent behavior. This approach leverages the *"Unity Game-engine's Navigation System"* to enable agents to perform actions related to movement.

Considering the assumptions listed in Figure 14, the combination of *BDI Architecture with Utility-Based Decision-making* is a robust approach for developing *AI Agent Systems* capable of making decisions autonomously and navigating dynamic environments such as construction site simulations. This approach allows for the implementation of:

- **Autonomous Navigation System**: Agents can intelligently and realistically navigate complex environments by using navigation systems that incorporate concepts like *"Navigation Mesh", "Pathfinding Algorithms", and "Dynamic obstacle avoidance".*
- **Decision-Making System**: The system integrates *Utility-Based Decision-making* to determine the most appropriate actions for agents based on task input data. By implementing actions as agent characteristics and calculating the utility of each potential action, agents can make informed decisions that balance multiple goals and constraints.

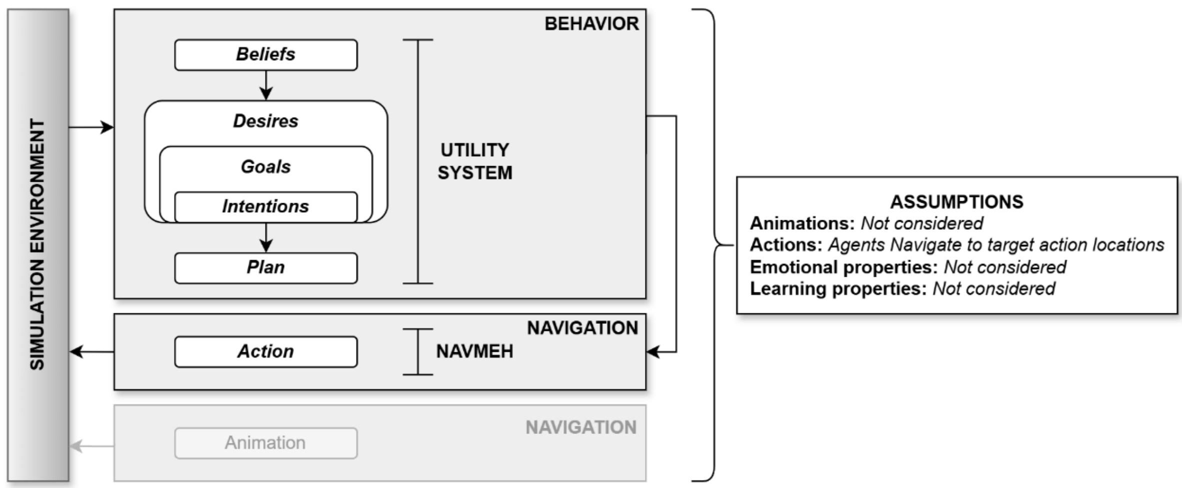


Figure 14 - BDI Utility Based Decision-Making architecture for agents' behaviour implementation in Advanced Simulation Model

Considering the same hypotheses, in this study an advancement with respect to the method described above is proposed, based on a hierarchical approach consisting of two decision-making levels to optimize agents' behavior within the construction site simulation model.

At the highest level of the decision-making system, the agent's behavior operates within a *"Finite State Machine (FSM)"* framework. In this system, decisions regarding actions are made in real-time based on the agents' current state within the simulation environment. Once an action has been determined, the *FSM* evaluates whether the agent has reached its designated location to perform the intended action. If the destination has not been reached, the *FSM* initiates navigation toward the specified location. These systems, accompanied by the navigation functions indicated above, allow agents to navigate complex environments intelligently and realistically.

This *FSM-based approach* ensures efficient and responsive agent behavior, enabling agents to execute tasks while adapting to the dynamic conditions of the simulation environment. It facilitates seamless integration of task execution and environmental interaction, enhancing the overall fidelity and realism of the construction site simulation (Figure 15).

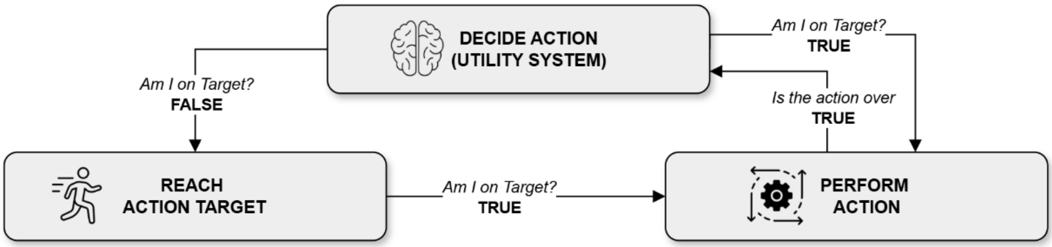


Figure 15 - Finite State Machine (FSM) framework proposed for agents' movements

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 in the context of its assigned task. In *Game AI or Decision-making Frameworks*, actions are evaluated based on specific criteria, as illustrated in Figure 14. For each *"Action"*, we can identify the so-called *"Considerations"*, which represent the factors or variables that influence the desirability or utility of different actions. These considerations reflect the key aspects of the game state or environment that affect the effectiveness of an action.

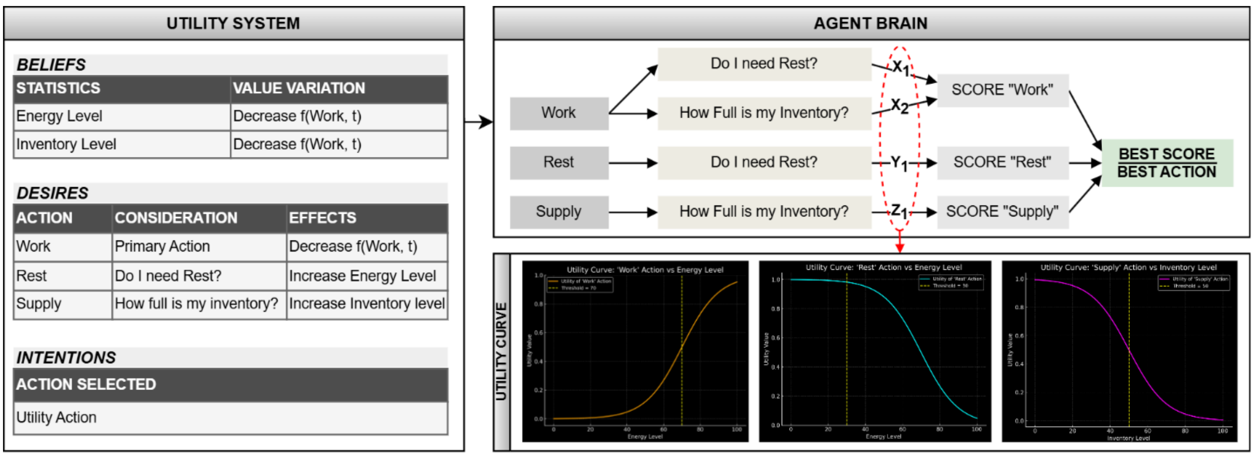


Figure 16 - Utility-Based BDI Decision-Making Model: Framework for autonomous agent behavior selection based on energy and inventory levels, supporting realistic task prioritization in construction site simulations.

By implementing these factors and variables, referred to as *"Consideration"* in Figure 16, as characteristics of the agent, also known as the agent's *"Internal State"*, the system calculates the utility of each potential

Action. This is achieved by mapping the relationship between *Actions, Statistics, Considerations* using "*Response/Utility curves"*, which quantify the interaction between the two. The utility of each *Action* is then computed based on this relationship. By integrating these *Considerations* into the *Utility System*, agents are able to make informed decisions that balance multiple objectives and constraints, ensuring optimal performance during the Advanced Agent-Based Simulation of site tasks.

This hybrid approach combines the strengths of both *FSM-based reactive control* and *Utility-based proactive decision-making*, significantly enhancing the autonomy and effectiveness of agents in the construction site environment. The *FSM* framework provides real-time responsiveness and ensures the efficient execution of tasks, while the utility system enables agents to prioritize actions strategically, taking into account long-term objectives and environmental factors. Together, these two levels of decision-making create a robust foundation for autonomous agent behavior, facilitating efficient task execution, coordination, and adaptation within the dynamic and complex construction site environment.

5.2.1.3 Hazardous events and risks rules

The goal of the *Advanced Agent-Based Simulation System* proposed in this framework is to identify and record data and properties related to hazardous events or situations occurring during the simulation, with the purpose of providing a risk estimate in the form of a heatmap displayed on the simulation model. In addition to the development of a recording system, the primary challenge lies in defining rules for modeling and representing hazardous situations within the simulation environment. This involves evaluating which situations can effectively be represented in the advanced modeling and simulation platform.

Starting with the definition of *Hazard (H)* (Table 1) as "*the intrinsic property of a situation, substance, or object, not influenced by external factors, which can cause harm and does not coincide with risk*", and considering the specific conditions identified as macro-factors influencing risk and safety during construction activities (Table 2), it becomes evident that *Objects, Substances, and Situations*—under specific conditions related to the environment, equipment, or workers—can trigger *Hazardous events*. Quantifying the likelihood of these occurrences helps estimate the risks associated with such events. In the context of construction sites, by excluding the consideration of substances and assuming optimal conditions for workers and equipment, the focus shifts to the following:

1. The **"Object"** refers to all entities previously categorized by their characteristics, including agents and static objects within the simulation environment.
2. The **"Situation"** refers to interactions and interferences among these entities, which, under specific conditions, increase the likelihood of hazardous events.

These situations are further exacerbated when site conditions are suboptimal. Factors such as poor site layout organization, inadequate positioning, improper sequencing, or the dislocation of site entities, defined during the planning phase, can significantly increase the likelihood of hazardous events. *Interference events*, caused by these suboptimal conditions, can often be effectively represented through *Collision*

Models within the simulation model. A collision model simulates physical interactions between site entities, such as *"workers", "machinery", and "static equipment"*, when they occupy the same space or come into contact with one another. These collisions, whether between moving objects (e.g., machines or workers) or between *Dynamic and Static Objects*, represent real-world interference scenarios that could lead to accidents or inefficiencies. By utilizing collision detection in the virtual environment, the simulation can mirror potential real-world hazards. For example, improper positioning of equipment could lead to obstructions in pathways, causing agents (workers or machines) to collide with static objects or each other. Similarly, poor sequencing of activities could result in overlap in space and time, increasing the risk of collisions. These collision models not only help in visualizing and predicting such interferences, but also to collect data for estimating the risk value of hazardous events, providing actionable insights for mitigating risks by adjusting site planning, entity positioning, and workflow sequencing.

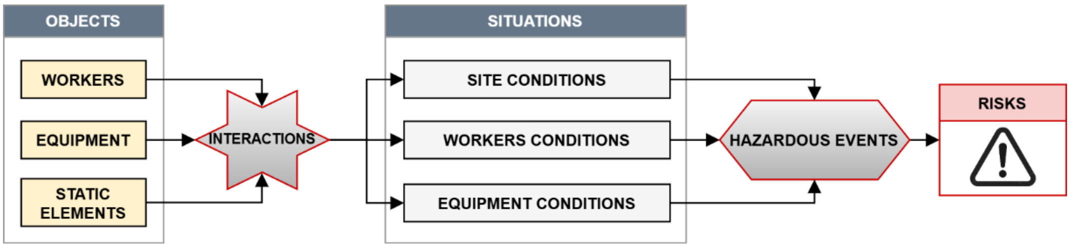


Figure 17 - Diagram illustrating Hazardous Event Generation Process where interactions between objects (workers, equipment, static elements) and site-specific conditions lead to hazardous events, which are then evaluated for associated risk levels.

Agent-Based Simulation of site activities is particularly well-suited for assessing collision situations due to its ability to model dynamic interactions between agents and their environment. By simulating the behaviors and movements of individual agents within the construction site and establishing rules for the representation of non-tangible elements, such as *Safety or Hazard Zones* related to *Static and Dynamic Site Entities* (Getuli, 2022), whether exposed or sources of danger, the system enables the detailed capture of agent behaviors, interactions, and collisions using advanced modeling and simulation platforms. The processing of collision data recorded during simulation, including coordinates, quantity, involved entities, duration, and other relevant information, provides valuable insights into the mechanisms driving *Risk exposure* within the construction site environment, that is heavily influenced by choices made during site design and activity planning, allowing for a more comprehensive understanding of potential risks

In addition, when considering *Autonomous Dynamic Agents* whose behavior is governed by a decision-making system, multiple simulations may yield different results in terms of agent behavior and, consequently, collision data. This variability arises because agents can make decisions and take actions based on different environmental inputs or internal states, leading to a range of possible interactions and collision scenarios in the same simulated environment.

By aggregating the results from multiple simulations of the same environment, we can gain a more comprehensive understanding of the likelihood of hazardous events. This approach allows for the estimation of the likelihood of specific risks occurring by analyzing the variation in *Collision Data* across different runs. The collection of diverse outcomes from autonomous agent behaviors enables a more accurate prediction of hazard occurrences, thereby refining the overall Risk Analysis.

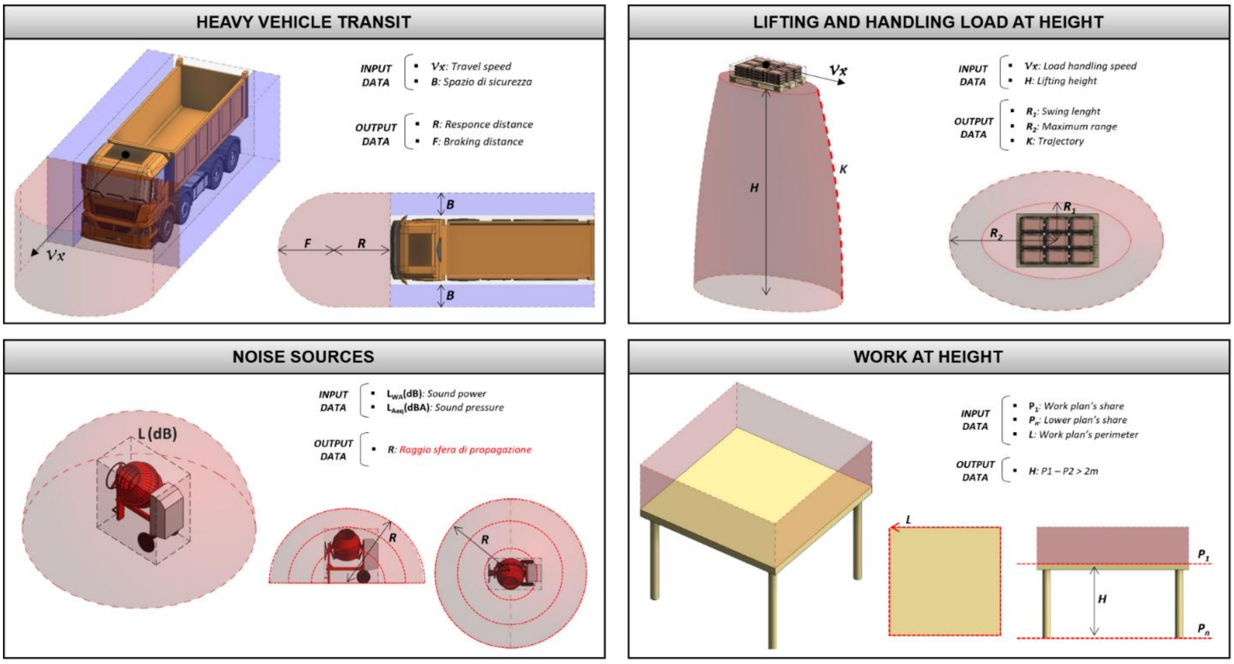


Figure 18 – Example of visual representation of different risk scenarios in construction, including heavy vehicle transit, load handling at height, noise sources, and work at height, with input and output parameters used to assess hazard zones and safety measures

Ultimately, this iterative process, where data from multiple simulations is combined, strengthens the likelihood estimates for hazardous events, while also contributing to the broader analysis of risk factors such as *Vulnerability (V)* and *Exposure (E).* By accounting for the dynamic and autonomous nature of agents, this approach ensures a more robust evaluation of risk, enabling decision-makers to anticipate a range of potential outcomes and implement more effective safety strategies.

5.2.2 Data Process Layer

In the development of our framework (Figure 2), the processing of data relevant to risk analysis, specifically *Vulnerability (V), Exposure (E), and Hazard occurrence (H)*, represents a crucial stage conducted within the **Data Processing Layer** during simulation execution. This phase involves the meticulous handling and recording of data essential for a comprehensive assessment of the simulation's dynamics, thereby supporting the overall risk analysis process. To better structure the methodology, At the core of the *Data Process Layer* and the developed system lies the execution of the simulation, which encompasses two primary actions: (1) **management of the visibility of components and agents** according to the sequence and duration of tasks set by the project schedule (Section [5.2.2.1]), and (2) **monitoring of agents and recording of collisions** (Section [5.2.2.1]). These actions are fundamental for accurately representing the progress of construction activities, capturing dynamic interactions, and storing interaction data in an accessible database for risk analysis.

5.2.2.1 Simulation performs

Reconstructing the dataset structure of each entity or 3D Object from the *Ifc* file enables the system to utilize the object's data for identifying external connections or, as in this case, directly leveraging 4D BIM data, specifically, previously unused "*Task Properties*" such as the planned duration and start/end dates.

These data are employed to establish rules for the system through a custom-developed "*Orchestrator script"*. The orchestrator is designed to reconstruct the sequence of activities and manage the visibility and appearance of simulation entities based on the project schedule and task timelines. This integration facilitates the dynamic reconstruction of construction sequences in alignment with the project timeline, providing a real-time visual representation of task progression.

To implement this process, several solutions can be adopted by leveraging the advanced capabilities of modeling and simulation platforms. The following points outline the main components, associated challenges, and potential methods for implementing these features:

- **Dataset Reconstruction and 4D BIM Data Utilization:** Extracting and organizing the data structure of each entity or 3D Object from the *Ifc* file is essential for leveraging *"Task Properties"* (such as *"Duration"* and *"Start/End dates"*) within the simulation.
  The dataset reconstruction (Section [5.2.1.1]) allows the system to directly use the 4D BIM data to manage the sequence and timing of activities. The use of custom scripts, developed in languages such as `Python` or `C#`, allows for reading and interpreting the properties of 3D objects and link them to the corresponding tasks, setting the stage for dynamic simulation.
- **Dynamic Management of Entity Visibility and Sequencing**: Managing the appearance and disappearance of entities in accordance with the project schedule requires synchronizing the simulation timeline with the sequence of activities.
  An *"Orchestrator Script"* can be developed to automate the management of visibility based on the schedule. This orchestrator uses an *Event-based System* to trigger the activation or deactivation of 3D objects as tasks progress, ensuring that entities appear or disappear in line with the construction phases.
- **Time Scaling and Real-Time Synchronization:** While the simulation timeline may need to be adjusted for visualization purposes (e.g., compressed or extended to speed up or slow down the view of the project), the integrity of real-time data collection must be maintained.
  A *Dual-layer time management approach* can be used, where a *Real-time clock tracks* critical events independently of the scaled visual timeline. This ensures that data such as collision monitoring or interaction tracking remains synchronized with actual task durations, enabling accurate data collection.
- **Implementation of an Interactive Timeline**: Navigating the project phases during simulation requires a flexible system that allows users to adjust parameters and view task progression over time.
  An *Interactive timeline* can be implemented, providing controls for navigating through different phases, with visibility triggers based on pre-defined dates and durations. This setup enables smooth transitions and accurate synchronization of entity activation and deactivation, even when adjusting time scaling.

These components together form a comprehensive framework that enhances the flexibility and accuracy of construction simulations enabling in-depth predictive analysis of construction site dynamics. The practical application of this system, along with its validation, can be observed in the *Test Model* discussed in Section [6.2.4] of this research, where the approach is tested and demonstrated in a real-world construction scenario.

5.2.2.2 Data collection

The second objective of the **Data Processing Layer** is to systematically record and collect data related to hazardous events identified during the simulation. Having previously defined collisions as possible Hazardous events, the primary focus is on Collisions between entities within the simulation model, which can be interpreted in the subsequent analysis phase to determine whether these collisions correspond to hazardous situations and assess their associated risk levels.

Detecting collision situations classified as hazardous within a simulation environment is indeed feasible. Simulation platforms provide robust capabilities for detecting and responding to such events in real-time. By utilizing the comprehensive knowledge of the simulation environment and its agents, including their spatial coordinates, properties, and behaviors, it is possible to implement collision detection algorithms or proximity checks to identify hazardous situations as they occur. The following key components outline the main aspects of the data collection process, providing methods applicable across different modeling and simulation platforms:

1. **Collision Detection and Data Logging**: Implement collision detection mechanisms using built-in physics systems or custom algorithms. Methods such as *"ray casting", "collision triggers",* or *"proximity checks"* can identify interactions. When a collision is detected, log pertinent data, including the agents involved, *"collision type", "coordinates"*, and other relevant attributes (e.g., *"speed"* or *"impact force"*). This information should be stored in structured formats (e.g., text file dictionaries) for subsequent analysis, allowing for detailed event tracking.
2. **Path Tracking and Movement Logging**: Record the paths taken by agents during the simulation to assess exposure to potential hazards. This can be achieved through "*Path-tracing techniques*" that log agent positions at regular intervals. A visual representation, such as a *"Line Renderer"* or equivalent, can depict paths within the simulation while storing the data in output files for later analysis. This helps to identify high-risk areas based on frequent agent movement and interaction density.
3. **Data Storage and Organization**: Organize and store simulation data systematically to ensure accessibility and traceability. Create a structured file system with separate directories for each simulation run, using timestamped filenames to maintain organization. Data should be stored in formats suitable for easy parsing and analysis (e.g., *.csv*), allowing for a hierarchical view of events and facilitating the identification of patterns across different scenarios.
4. **Visualization of Events During Simulation**: Implement *Visual Markers* (e.g., temporary-coloured spheres or lines) at collision points to aid real-time monitoring and verification of detected events. These markers should appear for a specified duration to ensure visibility and assist in understanding the context of collisions within the simulation.

A systematic approach to data collection, which involves adjusting simulation parameters, recording events during each run, and storing data in a structured manner, offers a comprehensive method for analyzing hazards and estimating the risk level of each task. The iterative analysis of diverse datasets allows for a more accurate understanding of dynamic construction site risks.

Following the key components outlined above, certain data have been identified as essential and useful for estimating the likelihood of hazardous event occurrence *(H)*, evaluating the severity *(V, E)*, and determining the overall risk level. The data collected during the simulation should include:

- **Identifiers of the agents involved in the collision**: This allows for tracking specific entities and understanding the types of interactions that may pose higher risks.
- **Type of collision** (e.g., *"machine/worker", "machine/machine", "worker/worker"*): Categorizing collision types helps to assess the severity of different interactions and their potential impact on safety.
- **Coordinates of the collision point** (e.g. *"CollisionPoint.x", "CollisionPoint.y", "CollisionPoint.z"*): Spatial information is crucial for analyzing where hazardous events are likely to occur within the simulation environment.
- **Environmental or agent-specific parameters** (e.g., *"Speed"* of the agents involved): These parameters provide insights into the dynamics of the collision, such as the forces involved, which can affect the severity of the event.
- **Coordinates of the paths taken by agents**: Recording agent movement helps in identifying areas of frequent exposure and potential hotspots for hazards.

By collecting these data points systematically, the simulation can provide a comprehensive dataset that supports a detailed analysis of risk factors, guiding the estimation of hazard occurrence probabilities and facilitating the creation of risk heat maps to visualize and mitigate potential dangers. The practical implementation of this approach, along with the validation of the collected data, is demonstrated in the *Test Model* section of this research (Section [6.2.4]). Here, the system's performance is tested in a real-world construction scenario, illustrating how the collected data contribute to accurate risk assessment and decision-making.

5.2.3 Data Visualization layer

The **Data Visualization Layer** represents the final phase of the simulation system, where collision data collected from previous simulations is processed to generate a three-dimensional risk map. This layer integrates and visualizes the analyzed data directly on the 3D model, using heatmaps to depict the distribution of risk throughout the construction site. The main functionalities of this layer consist of two key steps: *Risk Estimation*, which involves calculating risk levels using factors such as *"Hazard Likelihood (H)", "Vulnerability (V)"*, and *"Exposure (E)"* based on the recorded simulation data; and *Risk Heatmap Visualization*, where the calculated risk values are displayed on the 3D model through heatmaps, allowing for an intuitive identification of high-risk areas. As in the previous layers, advanced modeling and simulation platforms can implement custom scripts and functions to assign tasks to the system and carry out these processes effectively.

5.2.3.1 Risk estimation

Risk Estimation involves determining the risk factors for each area of the construction site based on data from collision events and agent movement. The process uses custom scripts to implement functions for the calculation of the following components:

- **Hazard Likelihood (H)**: Estimating the likelihood of hazardous events by analyzing the frequency of recorded collisions in each area. Functions can be used to assess this frequency and normalize the results for consistent likelihood scoring.
- **Vulnerability (V)**: Assessing the potential severity of incidents by considering factors such as the type of collision and the speed of agents involved. The scripts calculate vulnerability values to reflect the impact of different collision scenarios.
- **Exposure (E)**: Evaluating how often agents traverse specific areas, indicating the level of exposure to potential hazards. This is done by tracking agent movement data and computing exposure values for each grid cell.

The calculated values for *H, V*, and *E* are combined to estimate the overall risk level in each area. This approach enables a localized assessment of risk, allowing safety managers to identify specific zones that may require safety interventions.

5.2.3.2 Risk heatmap visualization

Risk Heatmap Visualization translates the calculated risk values into a visual format applied to the 3D model. The heatmap provides an intuitive representation of risk levels, enabling users to easily identify high-risk areas. Several general methods can be employed to create the heatmap:

- **Grid-Based Heatmap Generation**: The model is divided into a grid, with each cell representing a distinct area. Risk values are visualized using colour gradients, where different colours correspond to varying levels of risk.
- **Shader Techniques**: Shaders can be employed to dynamically colour the model's surfaces based on the calculated risk levels, allowing for real-time visualization.
- **Texture Mapping**: Applying a heatmap texture to the model surfaces, where the intensity of colour represents different risk levels, provides a straightforward approach to visualizing the data.
- **Dynamic Visualization Updates**: The system can adjust the heatmap in response to changes in the data, enabling real-time monitoring and visualization of risk as new information is incorporated.

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). By utilizing these methods, the system ensures that risk estimation and visualization are effectively implemented, providing safety managers with actionable insights. The application of this approach is demonstrated in the *Test Model* section [6.2.5], where the methodology is applied in a practical scenario to validate its effectiveness.

5.3 Module 3: Risk treatment and decision support

Module 3 represents the culminating phase of the proposed framework, where the primary objectives of the system are applied to enhance safety management on construction sites. This module focuses on utilizing predictive data derived from previous simulation stages to guide effective risk treatment strategies and optimize decision-making processes. By leveraging insights from heatmaps and data generated during simulations, the system provides a predictive analysis of the construction site model's operation, leading to actionable measures for improving site safety and project planning. In *Module 3*, the system reaches its main objective, offering support for understanding and contextually visualizing activity risk data to identify specific interventions and serve as a decision-making tool. The predictive insights gained here enable a targeted approach to addressing identified risks and refining construction site plans. The framework is designed to assist safety managers in implementing adaptive safety strategies based on data-driven predictions of hazardous events.

5.3.1 Application of predictive data for safety intervention

In this phase, the system supports safety managers and technical staff by providing heatmaps and detailed data from previous simulations to guide the development and implementation of safety interventions. The focus shifts from risk assessment to the execution of targeted measures aimed at enhancing on-site safety conditions, based on predictive insights obtained from the *Advanced Agent-Based Simulation System for risk estimation in construction activities*. The data provided by the analyzed simulation model enables informed decision-making regarding the implementation of specific safety measures and the evaluation of their effectiveness, as outlined below:

- **Mitigation of Hazards Using Heatmaps:** The heatmaps depicting risk distribution are analyzed to identify high-risk areas and prioritize safety interventions. The system assists in reorganizing workflows, adjusting equipment placement, or implementing additional protective measures in critical zones, based on the visual representation of risk levels.
- **Refinement of Safety Measures Using Simulation Data:** The effectiveness of previously implemented safety measures is evaluated by analyzing changes in risk levels across different simulations. The system supports the adjustment of interventions to ensure maximum safety impact, providing insights into how specific measures influence overall risk.
- **Optimization of Site Layout and Activity Planning:** Simulation data guides technical staff in making informed modifications to the construction site layout and the sequence of activities. The system enables the virtual testing of various configurations and plans, ensuring that changes are made with a clear understanding of their impact on risk levels.

Through these activities, the system facilitates the transition from data analysis to practical action, allowing technical staff to implement data-driven safety measures based on precise and detailed information. In doing so, not only are the safety conditions of the construction site improved, but a continuous improvement process is also fostered, where decisions are guided by simulations that can be highly realistic, providing a thorough and comprehensive understanding of risks specific to the construction site system.

5.3.2 Decision support for improvement in safety management

This phase focuses on supporting the technician in the continuous refinement of safety management strategies, integrating predictive simulation data into the decision-making process to enable a proactive approach to risk treatment. By incorporating new data and insights, the system allows safety managers to adapt practices as site conditions and risks evolve over time. The system supports several key activities that guide the technician in this phase:

- **Establishing an Iterative Feedback Loop**: The system facilitates a cycle of planning, simulation, evaluation, and adjustment, where modified scenarios are repeatedly simulated to provide ongoing feedback. This process helps the technician refine site plans and safety protocols based on real-time data from the virtual environment.
- **Conducting Scenario Analysis for Adaptive Safety Strategies**: The simulation environment is used to test different risk treatment strategies across various scenarios. This enables the technician to anticipate the potential outcomes of different interventions, allowing for the selection of the most effective course of action.
- **Utilizing Real-Time Risk Monitoring Tools**: A dashboard provided by the system visualizes risk levels using predictive data from the simulation. The technician can dynamically adjust site plans and safety measures based on evolving risks, supported by tools for ongoing monitoring and management.
- **Continuously Improving Safety Protocols**: Data-driven insights are used to enhance safety protocols, update guidelines, and implement new preventive measures. The system identifies high-risk areas from heatmap analysis, guiding the technician in tailoring safety measures to specific site conditions.

By emphasizing continuous improvement, the system enables site safety practices to remain dynamic and responsive, ensuring that safety strategies evolve in line with changing conditions and emerging risks.

6 Test Model

This chapter discusses the first implementation of the proposed *Advanced Agent-Based Simulation System for risk analysis in construction site activities*. The system aims to support decision-making and validate safety measures, as well as assess the planning and organization of construction site activities. A simplified pilot project has been used to demonstrate the system's development and functionality, providing a practical example of how advanced technologies like 4D BIM and Agent-Based Simulations can be leveraged to enhance risk assessment and safety management. The first part of this Section [6.1] focuses on the project setup and development of the 4D BIM model, presenting the creation of a simplified construction environment and task planning. The second Section [6.2] discusses the implementation of the Advanced Agent-Based Simulation System, covering agent behavior modeling, hazard management, and simulation execution. Finally, the third Section [6.3] evaluates the results and effectiveness of the implemented safety measures through an analysis of simulation heatmap data and collision occurrences. Together, these sections offer insights into the practical application of innovative technologies for improving the planning, scheduling, and execution of construction site activities. The aim of the system is to analyze the simulations of the construction activities identified in the following section to estimate the likelihood of occurrence of hazardous events, assess the exposure and vulnerability associated with these events, and identify the related risks and values.

6.1 4D BIM for Advanced ABMS

The pilot project developed for this study consists of a test model specifically designed to simulate a simplified construction site environment. The model involves two concurrent work activities ("*Work Activity 1", "Work Activity 2"*) carried out in adjacent spatial locations, representing typical tasks in a construction project (Table 6).

TEST MODEL PLANNING			
Work Activity A		**Work Activity B**	
Installation of Ground Floor Reinforced Concrete Columns, focusing on the formwork installation phase for casting.		*Brick masonry installation in the construction area where Activity A-type columns have already been built*	
Site Resources			
Labor brew	*1 work team consisting of 4 workers of the same level*	*Labor crew*	*1 work team consisting of 4 workers of the same level*
	Equipment	*1 shared truck*	
Site Requirements			
Area designated for the storage of materials and equipment necessary for the work.		*Area designated for the storage of materials and equipment necessary for the work.*	
General Requirements			
Area designated for services, refreshment, or rest			
Temporary site boundary; Area for material supply by vehicle.			

Table 6 - Test Model Planning: A Comparative Breakdown of Work Activities, Resources, and Site Requirements

These activities were chosen to reflect common site operations, such as structural installation and masonry work, allowing for the assessment of planning, resource allocation, and safety measures in a controlled setting. The setup includes associated *"Site resources"* necessary for executing the tasks and general requirements (*"Site Requirements", "General Requirements"*) essential for ensuring the proper functioning of the site and the overall construction process.

The project organization follows a *Work Breakdown Structure (WBS)* that aligns with the construction process model, enabling systematic categorization of both the project BIM 3D components and the construction site elements, as illustrated in Figure 19.

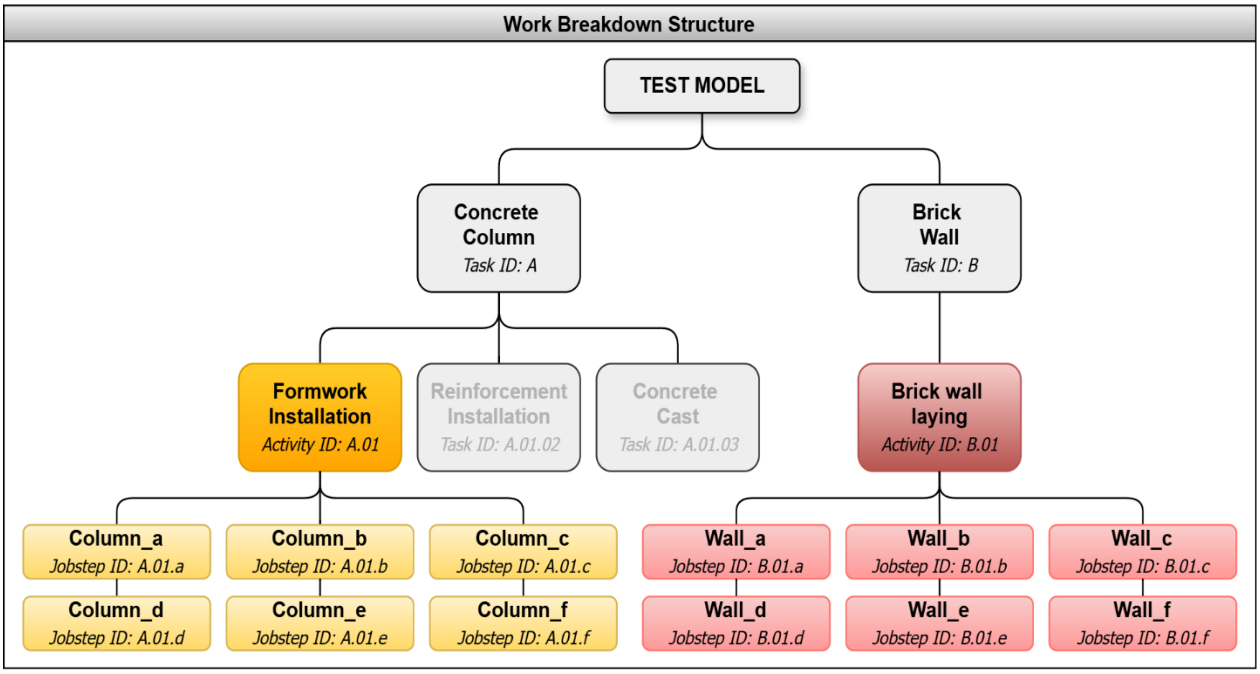


Figure 19 - Work Breakdown Structure (WBS) of the Test Model. This diagram illustrates the hierarchical organization of tasks for the construction of concrete columns and brick walls

The **3D BIM model**, created using *Autodesk Revit*, includes the static entities of the project and the construction site. These entities form the foundation for the simulation environment, with each component specified to meet the minimum data requirements for initiating the simulation, as previously outlined in Section [5.1.1.2]. The model includes both project-specific elements and general site resources, categorized under a standard classification system that defines their properties and roles within the simulation framework (Figure 20).

The **4D BIM model** extends beyond geometric modeling to incorporate detailed planning and scheduling of construction activities. Each activity is equipped with specific planning-related properties, such as duration, resource requirements, and scheduling parameters. Moreover, these activities are directly associated with distinct instances of the BIM model components to which they pertain. This approach ensures a direct connection between the project schedule and the physical elements within the model, facilitating the analysis of operational sequences, resource allocation, and task interdependencies.

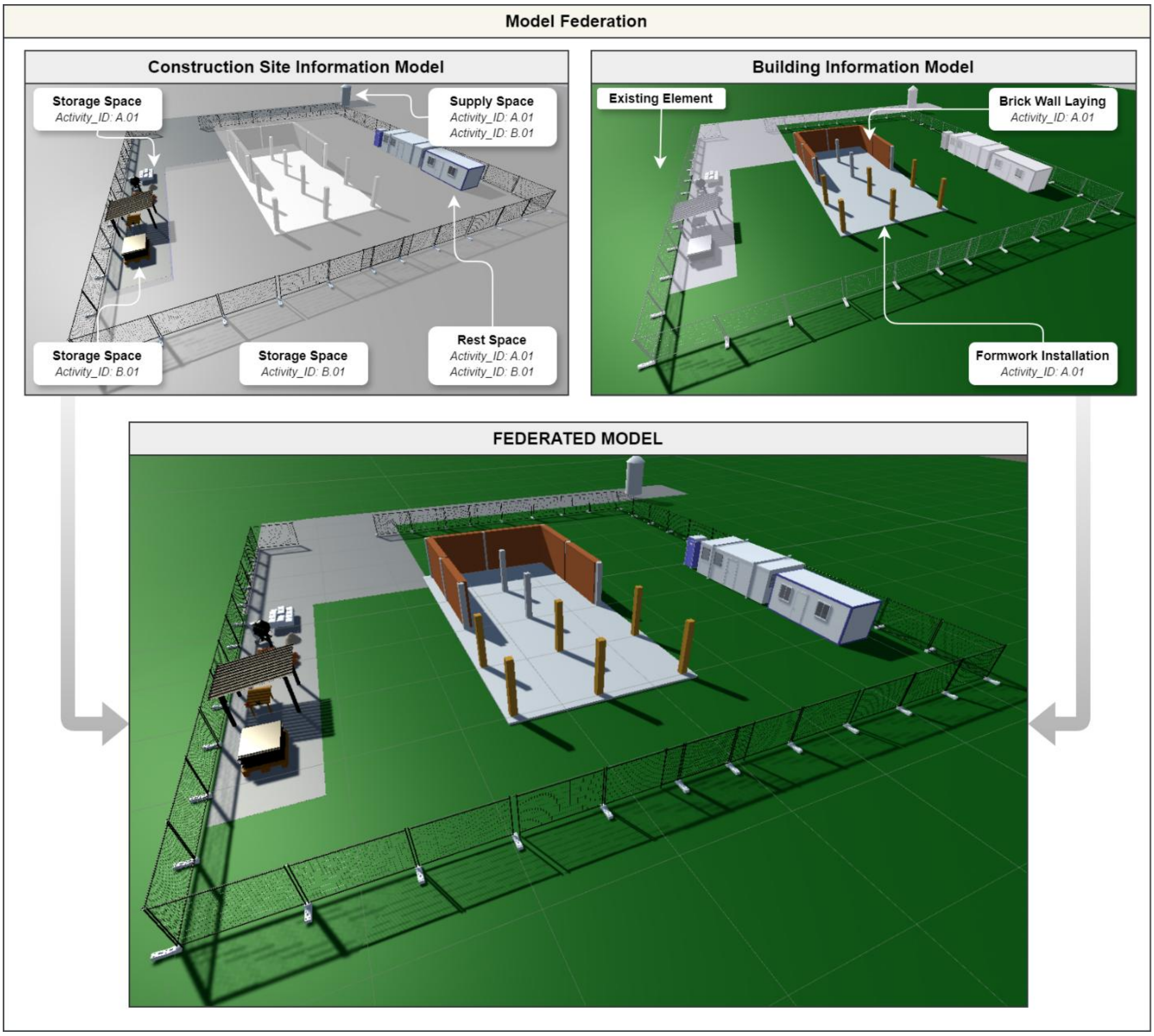


Figure 20 - Test Model Federation: Integration of Construction Site Information Model and Building Information Model

Dynamic resources, such as machinery and workers, are integrated using *Synchro Pro*, where the identified tasks (Figure 21) are implemented with the planning properties previously defined, referred to as Task Properties (Figure 11). While various software tools, including *Synchro Pro*, provide libraries of 3D resources for construction elements, the decision was made to represent these resources as data only in the BIM model. This strategy delegates the instantiation of the *3D Resources Components* to the developed *Advanced Simulation System*, which is better suited for generating and managing the visual representation of these dynamic elements during the simulation process.

For the simulation system to effectively utilize the developed 4D BIM model, the data must be exported in specific formats compatible with advanced Agent-Based Simulation. The model was exported in the following formats:

- **IFC format:** This format includes geometric and informational content related to the model components, capturing essential data such as Identity Properties and link properties.
- **CSV format:** This format encompasses information associated with construction tasks, including *"Task properties"* like scheduling data.

Figure 21 - Activity Sequence and Task Properties Visualization of the Test Model 4D BIM

The use of *.Ifc* and *.csv* formats is a standard practice in 4D BIM modeling, ensuring accurate integration of data into the simulation system. These formats were chosen to enable system interoperability with BIM-based design processes, even though not all advanced modeling and simulation platforms provide native interfaces for importing these formats. By adopting *.ifc* and *.csv* format, this approach ensures that project information is accessible and compatible with a variety of tools used in BIM processes, allowing the import of links between geometry and semantic information into the model, and enabling the system to leverage these data for conducting *Advanced Agent-Based Simulations for Risk Analysis of site activities*.

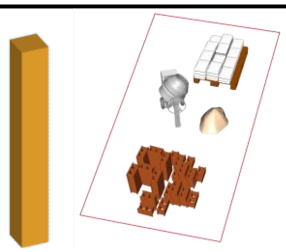
IDENTITY PROPERTIES			
Geometric content	**Name**	**Property Type**	**Data Type**
 *Example of Static Object Geometric content*	*Category*	*IfcPropertySingleValue*	*IfcText*
	Element Type	*IfcPropertySingleValue*	*IfcIdentifier*
	LINK PROPERTIES		
	Name	**Property Type**	**Data Type**
	Mark	*IfcPropertySingleValue*	*IfcIdentifier*
	Activity ID	*IfcPropertySingleValue*	*IfcIdentifier*

Table 7 - Custom Property Set developed for the organization and IFC export of the minimum informational content identified as necessary for the use of the advanced simulation system

6.2 Advanced Agent-Based Model and Simulation of site activity

This section presents the core of the developed and tested Advanced Agent-Based Simulation System, detailing its technical and methodological aspects. The chapter delves into all critical components, illustrating the implementation and operation through the analysis of a specific construction site model introduced in the previous section. The content is organized into the following key topics:

- **Selection of the Advanced Simulation Tool:** This part outlines the criteria and process used to select the advanced simulation tool for the system's development, considering factors such as handling complex agent-based models, scalability, integration with BIM data, and the capacity to simulate dynamic construction site environments (Section [6.2.1).
- **Integration of the system in the safety management process:** Through the development of a *BPMN diagram*, the integration of the proposed Advanced Simulation system with the safety management process during the planning phase of a construction site is illustrated, outlining the major steps where the system provides support to safety management and planning activities (Section [6.2.2]).
- **Agent-Based Model Creation:** The simulation environment is built based on data from a 4D BIM model, representing the construction site's components, physical spaces, and the sequence of activities over time. Agents, representing entities like workers, machinery, and materials, are defined based on BIM data and configured with specific attributes and behaviors that guide their interactions within the environment (Section [6.2.3]).
- **Implementation of Dynamic Agent Behaviors and Hazard Management:** The development of a behavior library for agents is discussed, including responses to various stimuli in the construction environment. Hazard management strategies are implemented to enable agents to recognize and respond to potential risks, assessing how these affect daily operations and planning mitigation strategies (Section [6.2.3]).
- **Execution of the Agent-Based Simulation:** The procedures for running the simulations are detailed, including configuration settings and control parameters, with iterative executions performed to ensure the reliability of results. Data on agent performance and site dynamics are collected, structured, and stored for analysis (Section [6.2.4]).

- **Simulation Data Analysis and Results Visualization:** Data analysis methodologies used to interpret the collected information are explained, focusing on pattern identification, performance evaluation, and risk assessment. The analysis results are visualized using advanced tools that facilitate understanding of site dynamics and highlight areas for improvement (Section [6.2.5]).

The system architecture is designed for scalability and flexibility, allowing it to adapt to various construction site configurations and BIM models through configurable parameters and a modular approach. This ensures:

- **Ease of Adaptation:** The system can be quickly reconfigured for new construction sites by modifying BIM model parameters and updating the agent library.
- **Component Reusability:** Reusable system components across different projects reduce development time and costs.
- **Process Automation:** Automation of much of the configuration and execution process enhances analysis efficiency and accuracy.

The proposed Agent-Based Simulation system represents a novel approach to risk estimation in construction activities, offering significant potential to improve safety and operational efficiency.

6.2.1 Evaluation and selection of simulation tools

The selection of the simulation tool was guided by several key criteria: the ability to handle complex agent-based models, scalability, seamless integration with BIM data, and the capability to simulate dynamic and realistic construction site environments. A thorough comparison was conducted, considering tools such as *Unreal Engine*, *Unity 3D*, and *Nvidia Omniverse*. The evaluation focused on computational efficiency, user interface, flexibility in modeling agent behaviors, and support for advanced data analysis.

Unreal Engine stood out for its high-quality graphics and powerful rendering capabilities, while *Nvidia Omniverse* offered robust support for collaborative workflows. However, both tools posed challenges in integrating with BIM data and meeting the specific requirements for agent-based modeling in construction settings. *Unity 3D* emerged as the most suitable option for the project due to several advantages:

- **Ease of Integration**: Unity supports robust integration with BIM data through various free plugins and *APIs*, enabling the seamless incorporation of detailed construction site models.
- **Flexibility and Customization**: Its architecture allows extensive customization, making it suitable for developing specific agent behaviors and environmental interactions required for simulations.
- **Community and Support**: Unity has a large and active community, with comprehensive documentation and support resources that facilitate troubleshooting and further development.
- **Performance and Scalability**: The tool provides excellent performance in managing complex simulations, efficiently handling large-scale construction sites with numerous agents.
- **Cross-Platform Capabilities**: Unity supports deployment across multiple platforms, including desktop, mobile, and VR, increasing the versatility and accessibility of the simulation tool.

- **Cost-Effectiveness**: The tool is cost-effective, with flexible licensing options, making it suitable for both current and future projects.

These factors collectively made Unity 3D the optimal choice for creating an Advanced Agent-Based Simulation tool for construction site activities, ensuring the system met all project requirements and provided a solid foundation for scalability and future enhancements.

In this research, the decision was made not to develop a standalone tool to avoid dispersing efforts on tool building. Instead, the focus was directed toward developing and evaluating specific aspects of the proposed advanced simulation system. Although the system was not built as a complete tool, it was structured into three Unity scenes that represent components of a future tool: a "**Setting Scene**" where users can implement the model, interact with the simulation (Section [6.2.3]), and configure all aspects of the Agent-Based Simulation for construction activities; a "**Simulation Scene**" designed for visualizing the simulation and producing results (Section [6.2.4]); and a "**Visualization Scene**" where users can view outcomes related to specific construction activities of interest (Section [6.2.5]).

6.2.2 Evaluation of the Integration of the Advanced ABMS System in the Construction Safety Management Process

To assess the effectiveness and delineate the features of the proposed simulation system, a workflow was developed using the *Business Process Model and Notation (BPMN)* standard (Figure 22). This *BPMN* diagram visualizes the various stages of the safety management process during the planning phase, including decisions related to the design, organization, and scheduling of the construction site and work activities. The diagram highlights where the proposed simulation system integrates into the workflow, showing the key decision points and steps where it provides support by validating the planned measures against specific risk conditions associated with the activities.

The *BPMN* representation also outlines the main interactions and sequences of the planning process, illustrating how the simulation system leverages 4D BIM project data to inform safety management decisions. By integrating these data inputs, the system conducts a comprehensive risk analysis and assessment, providing valuable outputs that guide safety management decisions and align them with evolving project requirements. This approach aims to optimize safety management by enhancing the efficiency and accuracy of decision-making during the planning phase.

The approach presented in the BPMN enables effective integration of the Advanced ABMS System into the safety management planning process by combining 4D BIM data with agent-based modeling. The workflow highlights the key stages of planning where the system provides support, allowing for the analysis and validation of site organization and activity sequencing to mitigate risks. For example, with the data provided by the 4D BIM model, the system can assess site layout and identify potential conflicts or interferences among resources, such as machinery and workers, based on their positions and operational schedules.

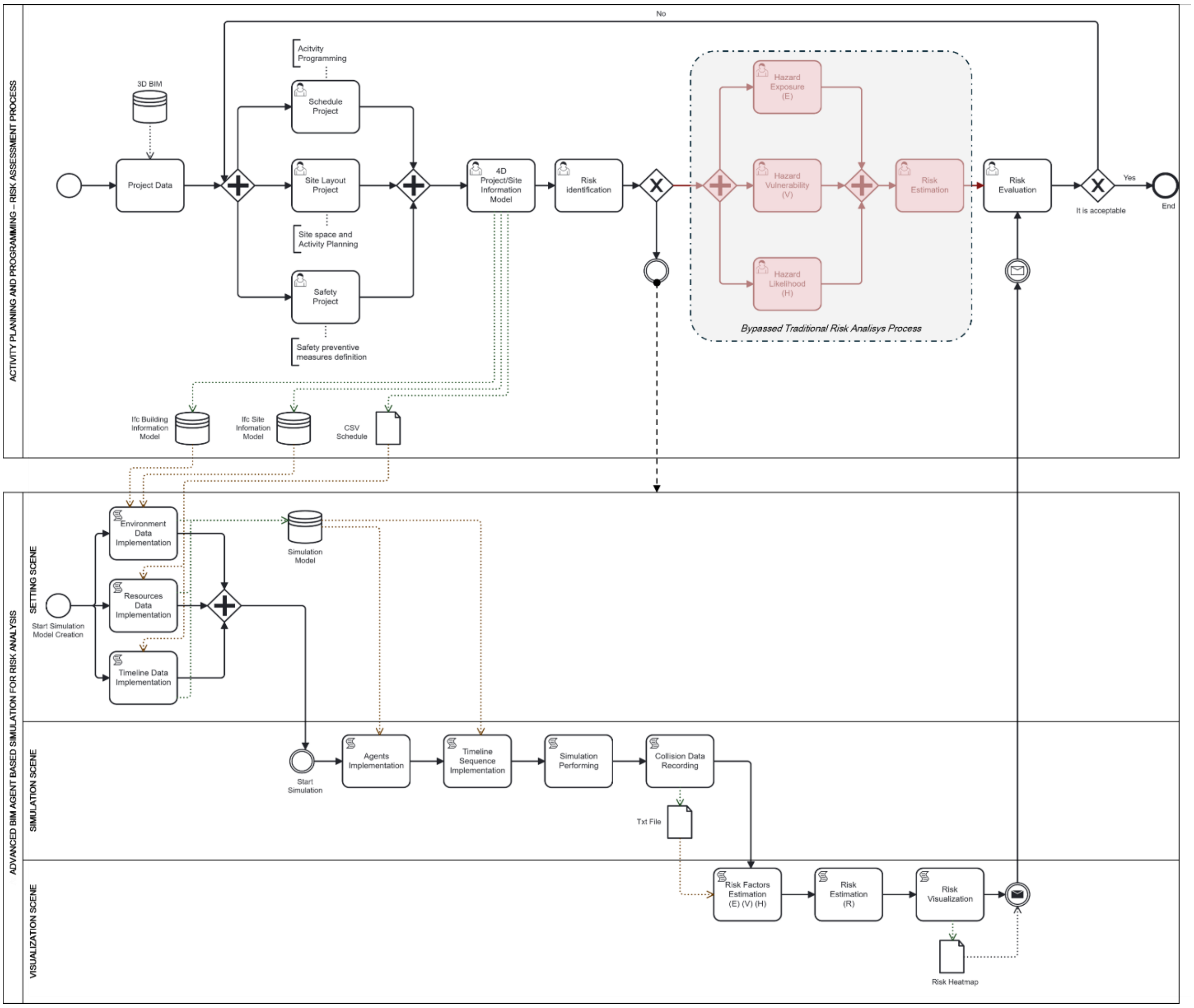


Figure 22 - BPMN of Risk Assessment process with support of Advanced BIM Agent Based Simulation System for Risk Analysis

The system's structure is divided into three main scenes, which play a crucial role in ensuring integrated and dynamic safety management (Figure 23). The *"Setting Scene"* enables the configuration of the simulation environment and the implementation of agent and resource data, thus providing an accurate foundation for starting the simulation. During the *"Simulation Scene"*, the system executes the simulation itself, collecting relevant data on interactions and risk conditions occurring within the model. Finally, the *"Visualization Scene"* displays the results of the risk assessment through a heatmap, offering a clear representation of risk-prone areas within the construction site.

This iterative process, where data collected at each stage is used to continuously improve planning and safety management, allows for a more comprehensive understanding of potential risks. The system not only provides predictive risk analysis but also enables site managers to make preventive adjustments to the layout and sequencing of activities, enhancing the overall effectiveness of risk mitigation strategies. Through this approach, the system facilitates a more in-depth analysis of risk factors and supports more informed and targeted safety management decisions.

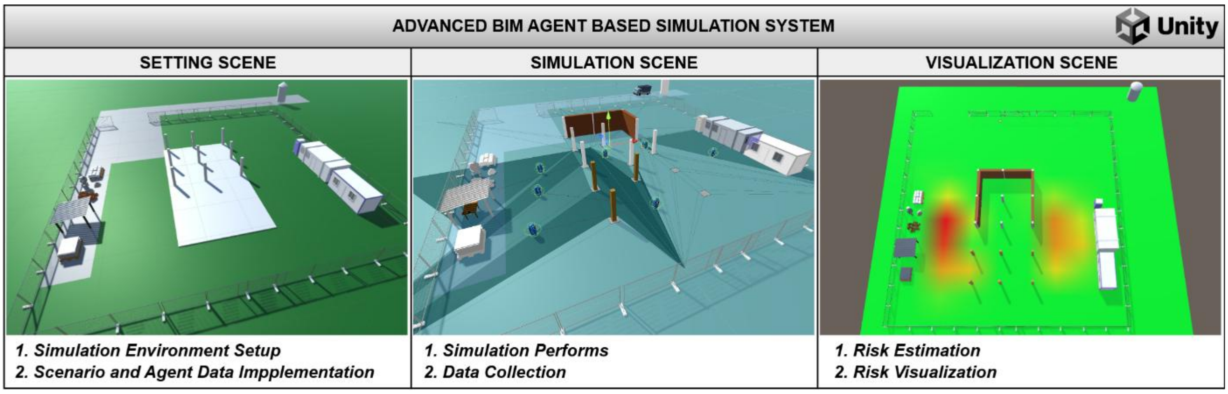


Figure 23 – Overview of the System scenes structure proposed

In the subsequent sections, all system activities will be detailed, including the development choices made and the operational functioning of the system, leading up to the execution of each step. This analysis will provide an in-depth view of the process, highlighting how the system contributes to on-site safety management and ensuring that design and organizational decisions are adequately supported and validated against potential risks

6.2.3 Setting Scene

As shown in Figure 22, the *Advanced Agent Based Model and Simulation System* is structured into three lanes corresponding to distinct scenes developed for user interaction, each implementing specific processes within the advanced simulation framework. The first Scene represents the sequence flow, events, and activities undertaken by the system to generate the agent-based BIM simulation model. Following the presentation of methods for importing the Ifc project and construction site models into the system, the steps involved in the first scene will be discussed in detail.

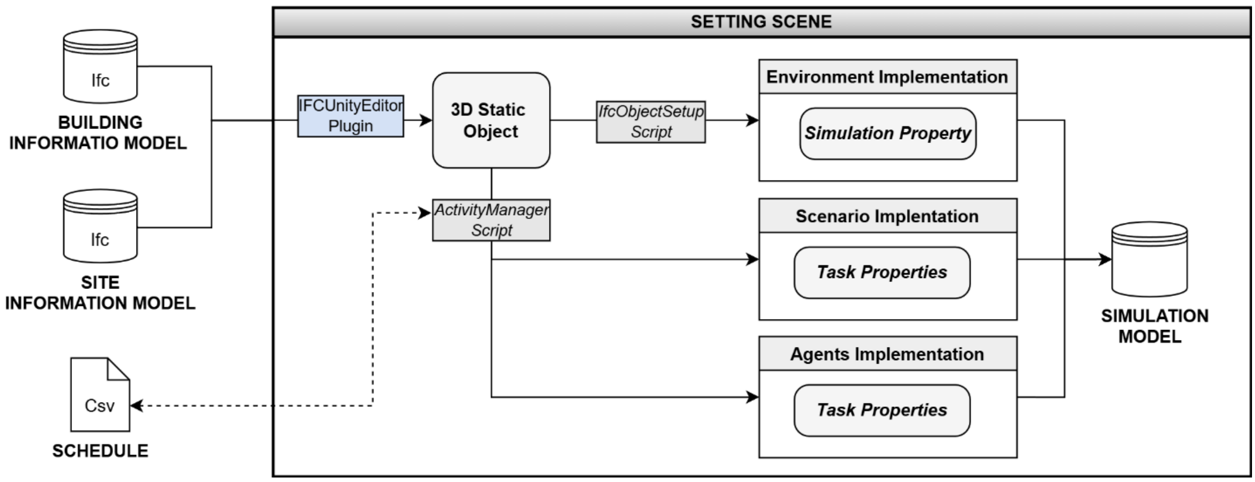


Figure 24 - Workflow for Setting the Simulation Scene within the Advanced BIM Agent Based Simulation System

The subsequent sections will cover key aspects of setting up the simulation environment and implementing the agent-based model. **Simulation Environment** (Section [6.2.3.1]) outlines the initial steps, including importing static entities and implementing navigation and collision functions to reconstruct the 4D model's geometry and data within Unity. **Scenario and Agents Data Implementation** (Section [6.2.3.2]) describes how the system uses task properties and scheduling data to create specific simulation scenarios for various construction activities, populating these scenarios with agents from a pre-defined library (Figure 24). This section also covers the development of the *Site Autonomous Agents Library*, which includes the physical, behavioral, and hazard modeling of agents, ensuring realistic interactions within the simulation environment. Finally, it addresses *Hazardous Representation*, focusing on identifying collision risks for using these data to support safety management and preventive measures throughout the construction process.

6.2.3.1 Simulation environment

As outlined in the preceding sections, the process begins with the availability of the project and construction site 4D BIM models. Within the **Simulation Environment**, specific scripts have been implemented to achieve and automating two main tasks: (1) transferring the geometric and informational content of the 4D BIM model into the simulation platform, and (2) converting these elements into components of the simulation model by assigning simulation properties. These properties include physical characteristics that enable the realistic representation of behavior and functions within the platform, allowing for accurate simulation of the components' real-world dynamics. Utilizing the various file formats exported from the 4D BIM model. The steps taken are presented in detail below:

Static Entity Import

The initial phase involves transferring the essential contents identified in Section [5.1.1.2], reconstructing the three-dimensional geometric, informational, and semantic structure of the 4D model within *Unity*. It was chosen as the game engine for system development due to its capability to handle complex 3D simulations. Although a custom system for importing IFC models into *Unity* was initially considered, the availability of advanced plugins *(APIs)* and significant progress in the field led to the choice of the "*IFC Unity Editor Plugin"*, recently developed by the *Chair of Intelligent Technical Design (IDT)* at the *Bauhaus-Universität Weimar, Faculty of Civil Engineering*. This plugin efficiently imports both the 3D geometric data and associated information from the IFC model. In this scene, the execution of the Plugins import function allows the following steps to be performed automatically:

1. **Importing the 3D Content of the IFC Model:** The plugin reconstructs the geometric structure of the IFC model, preserving the dimensions, shapes, and spatial relationships between elements. This process ensures that all physical components of the construction site are accurately represented within the *Unity platform*, maintaining the original design's integrity and fidelity (Figure 25).
2. **Importing the Informational Content of the IFC Model**: Alongside the geometry, the plugin imports the semantic information associated with each component, such as material properties, classifications, and in particular the *PSet* containing "*Identity Properties" and "Link properties"* (Table 7). The 4D BIM information related to scheduling tasks is managed using a separate text file exported directly from the scheduling software, rather than being imported as part of the game-object properties. This external source allows the system to link task-specific information to game-objects through common parameters shared between the game-objects and the scheduling file. By maintaining the scheduling data externally, the system enables dynamic updates; any changes to the project timeline can be

easily reflected by modifying the scheduling software and updating the corresponding text file without the need to reimport the entire model, as better indicated in Section [6.2.3.2].

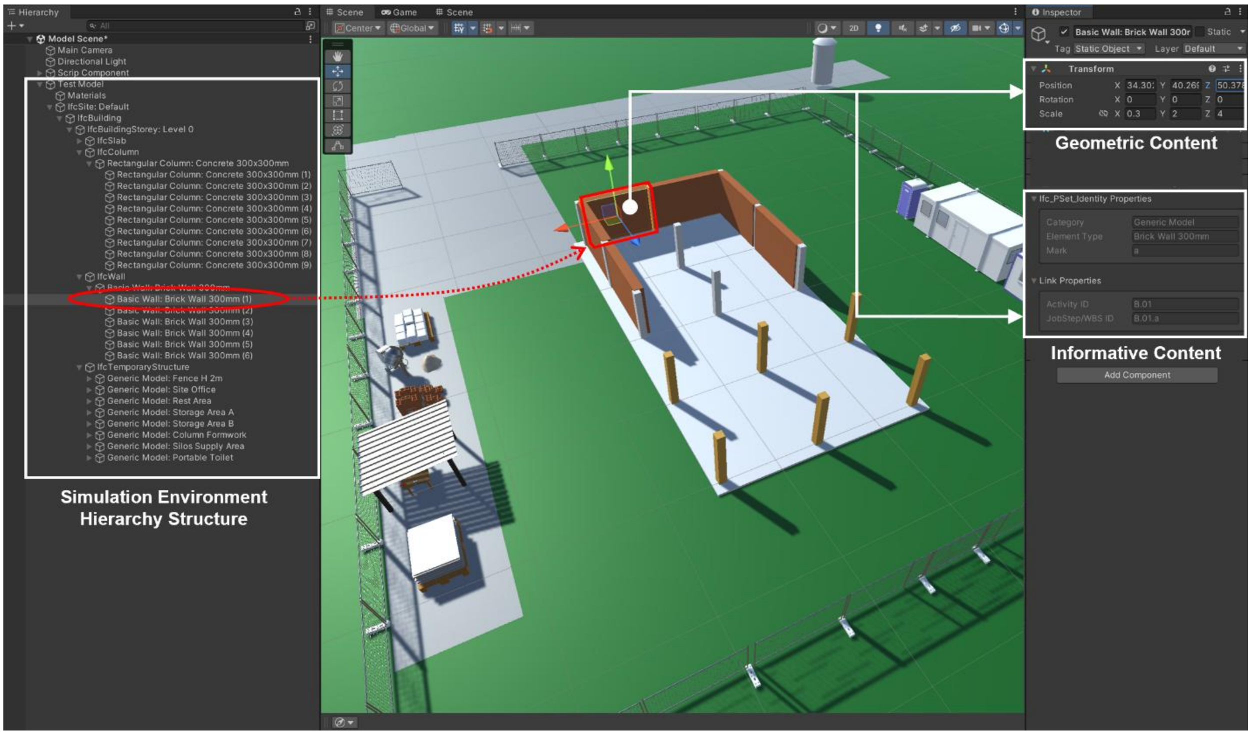


Figure 25 – 3D Static Entities hierarchy structure and first informative content implementation

This approach allows for the transformation of the BIM model into an advanced platform like Unity Game Engine, forming the foundation of the system's process and enabling its use like advanced simulation model. Additionally, by managing 4D BIM data externally, the system ensures adaptability, allowing for seamless synchronization of the simulation with evolving project schedules without the need for repeated model imports.

Simulation property implementation

Once the model components and data are imported, a custom script named "IFCObjectSetup" is employed to automatically process all static entities within the model. This script is attached to a dedicated, hidden component within the scene, which serves as the manager for enhancing the imported objects. The script performs the following tasks when the simulation begins:

- **Automatic Tag Assignment**: The script identifies all Game-Objects originating from the IFC model that possess a specific Property Set and assigns them the tag "Static Object." This tagging system helps differentiate these objects from other elements in the Unity scene, such as control or management scripts.
- **Assignment of Navigation Properties**: For each static object, the script adds navigation properties by attaching a NavMeshObstacle component. This component enables the simulation to account for the presence of obstacles during navigation, allowing navigation agents to interact correctly with the environment. The NavMeshObstacle configuration also includes enabling the carving option, which allows the navigation mesh to dynamically update as objects appear or disappear in the simulation.

- **Management of Physical Properties**: The script assigns a *"Rigidbody Component"* to each 3D Object, setting characteristics such as *"mass"* and *"kinematic behavior"*. This ensures that the *Static Objects* are correctly integrated into the simulation's physics system, simulating realistic interactions between construction site components without being affected by external forces.
- **Collision Handling**: The script adds a *"Collider Component"* to the static objects if one is not already present. This enables the detection and management of collisions, which is essential for tracking potential interactions or conflicts between entities in the construction site environment. The script uses a default *"BoxCollider"*, but the type of collider can be customized as needed.

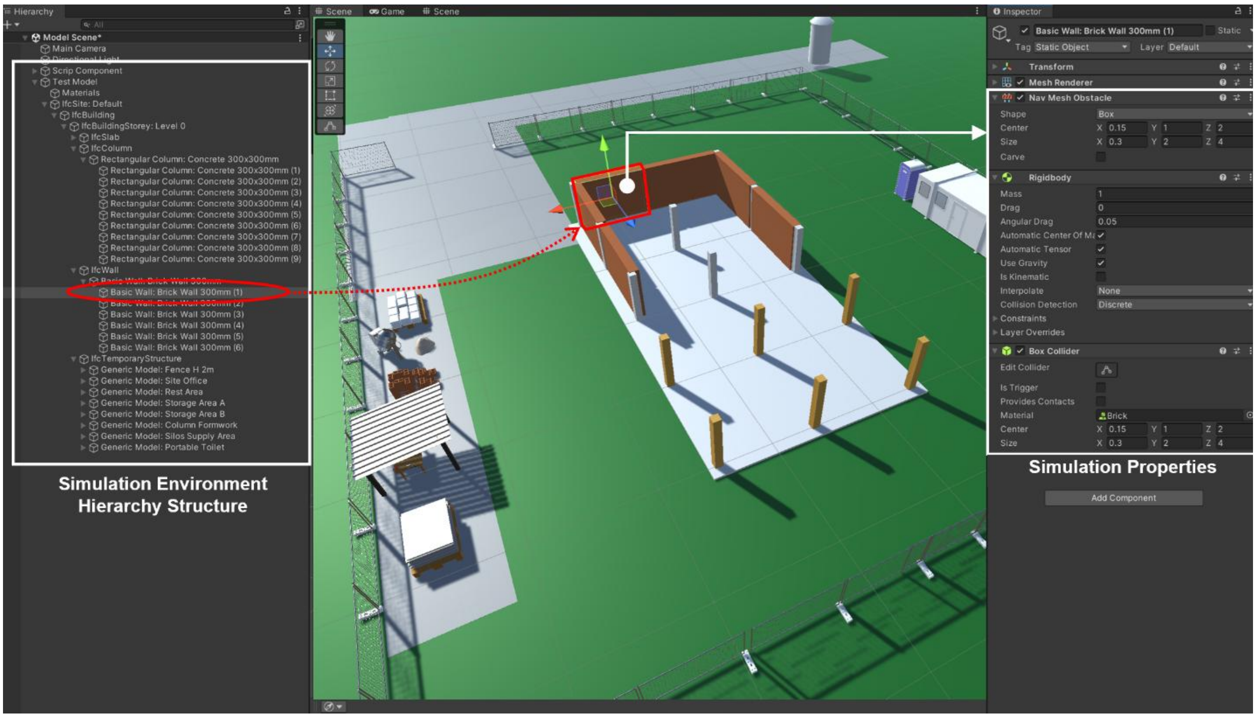


Figure 26 - 3D Static Entities hierarchy structure and Simulation Properties implementation

The use of the *IFCObjectSetup Script* automates the process of preparing the imported IFC model for advanced simulation. By systematically assigning navigation, physical, and collision properties to the static entities, the script transforms the imported BIM model into a fully interactive simulation environment (Figure 26). The informative content linked to each object (such as metadata from the *Property Set*) provides a foundation for identifying the 4D BIM data, which can be used for linking task-specific information and conducting detailed risk analysis of construction activities.

6.2.3.2 Scenario and agent data implementation

Given the three-dimensional simulation environment consisting of the *3D Static Object* of the project and construction site, at the start of the simulation, the developed system utilizes the information content of the *3D Static Objects* to read the task properties of each entity and create the corresponding simulation scenarios for each activity. This process involves two main phases that are implemented in the present scene but are activated in the simulation scene to perform it:

- **Scenario Data Implementation**: This phase involves the transfer of 4D content into the static entities of the model. This data fuels the system for creating the construction sequence from the schedule, implementing agents and their directives, as well as managing the visibility of *Static and Dynamic Object* in relation to the duration of activities.
- **Agents Data Implementation**: Following the configuration of the 4D data on *Static object* in the previous phase, this data is processed to create instances of *Dynamic Object/Agents* within the system. Information pertaining to the *Static Object* involved in the activity, as well as its *"Sequence"*, *"Duration", etc.* is encapsulated as properties of these agents. Once established and categorized in a library of autonomous construction site agents, they are made available to the system for implementation and operational use during the simulation.

Subsequent sections will detail the development and functionality of the tasks corresponding to these phases, as delineated in the preceding *BPMN* diagram.

Scenario data implementation

In the system's *Setting Scene*, a sophisticated 4D BIM data reading system is implemented through a control Game-Object named *Activity Manager*. This component scrutinizes and transcribes scheduling data from the simulation model's entities, setting the stage for effective simulation phase management. The `ConstructionManager Script` plays a critical role in this process by creating a uniform data structure within each *Static Object Inspector* of Unity. The script uses *"WBS ID"* as a key identifier to accurately associate schedule entries value with the 3D Static Object with corresponding *"JobstepID"*, ensuring that each object of the Advanced Simulation Model is populated with the relevant data tailored to its specific task requirements. This script is meticulously designed to manage *"Task Properties"* for each object, tagged as *StaticEntities*, which represent static model entities in the simulation (Figure 27).

The script operates through several distinct but interconnected steps:

1. **Data Structure Initialization**: Initially, the `ConstructionManager Script` evaluates each object within the simulation environment to ensure it is equipped with the necessary data structures to hold scheduling information. If an Object lacks the *Task Properties Component*, the script automatically initializes this component, setting the foundation for data storage directly within the Unity Inspector. This step is crucial for maintaining uniformity and ensuring that all relevant entities can store, and display *Task Properties* classified as *"Scenario Data"* and *"Agents Data"* effectively ().
2. **Data Loading**: When updates in the inspector in the field of link file, are detected, the script loads data from the specified *Text Asset*. It supports various file formats like *.csv, .txt, .xml*, parsing the data line by line to extract essential details such as *"WBS", "Description", "Start/End Date", "Activity Type"* and *"Duration"*. This parsed data is temporarily stored in an array or list, poised for the next step of data population.
3. **Data Population**: With the data parsed, the script then matches each data entry with the appropriate 3D Object based on the *"Activity ID"* values. It populates the *Task Properties Component* of each

matching *Static Object* with the extracted data, thereby ensuring that the information is stored and made visible in the *Unity Inspector*. While this process prepares the *Static Objects* for use in the simulation, the actual orchestration of the simulation based on these data values will be handled by a separate script that runs during the simulation scene. This subsequent script will control how the simulation reacts to the populated data, including task timings, visibility of components, and other dynamic interactions.

4. **Real-time Data Update Detection**: Leveraging Unity's `OnValidate()` method, the script remains vigilant for any changes made to the linked data file directly from the *Unity Inspector*. This responsiveness allows the script to reload and repopulate data seamlessly, ensuring that the simulation remains accurate and up to date with any modifications in the scheduling data.

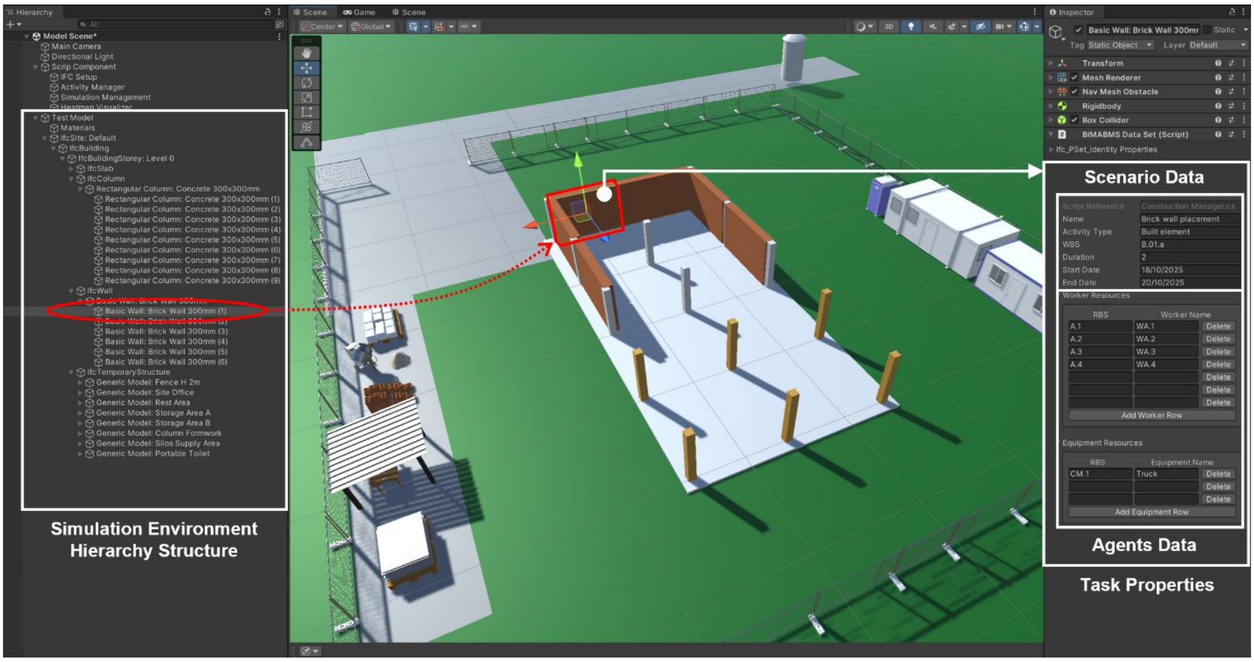


Figure 27 - 3D Static Entities hierarchy structure and Task Properties implementation

While the `ConstructionManager Script` ensures that all static entities are initialized and populated with accurate task data, it sets the stage for the simulation but does not control the actual runtime behaviors. A separate orchestration script will act during the simulation scene to synchronize these populated data fields with the ongoing tasks, adjusting the timing, visibility, and other attributes of *Static Objects* accordingly.

Site autonomous agents library

Before the agents implementation phase and the simulation execution, it was necessary to create the *3D Objects* corresponding to the **Agents** (i.e., the digital twins of construction site resources) to be stored in a library from which the system can draw during agent implementation. Like BIM libraries, the development of a comprehensive and open library of construction agents would promote and simplify the system's use. A continuously updated and optimized library ensures greater reliability and efficiency for different construction projects, making the system more versatile and widely applicable.

In this initial test of the system, a dedicated library was developed in *Unity*, where only the agents relevant to the test model activities were created. The *Dynamic Object* already modeled in the 3D and 4D BIM models were excluded, and instead, their task-related information was used from the schedule. The *Agents* modelled for this test include the *"Worker"* and the *"Supply truck"*.

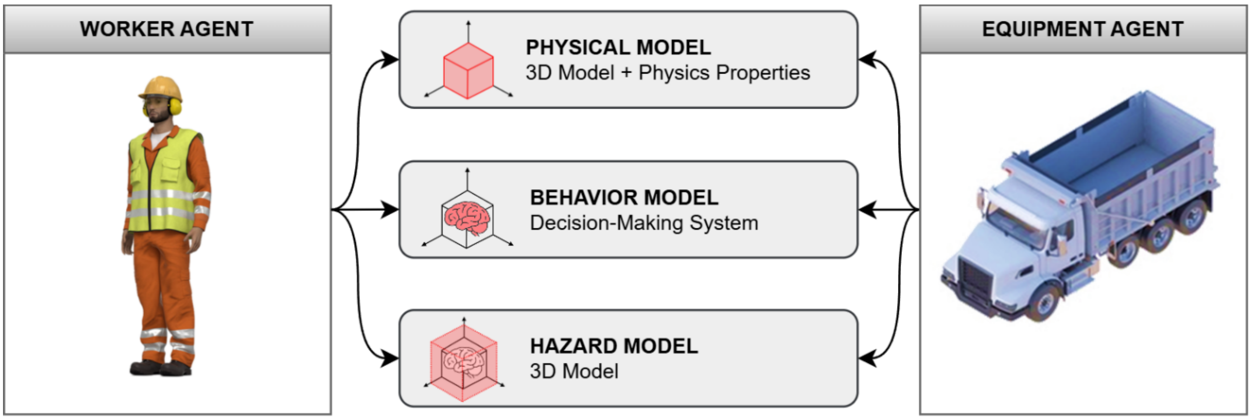


Figure 28 - Key aspects for agent modeling in the Advanced BIM Agent Based Simulation System

For each agent type, the following aspects were defined (Figure 28):

- **Physical Model of the Entity**: The *3D Representation* and *Physics Properties* of the agent were defined to ensure realistic interaction within the simulated environment. This includes the agent's *"mass", "friction"*, and *"resistance characteristics", etc.,* which are essential for simulating realistic movement dynamics and interactions.
- **Behavioral Model of the Entity**: The agent's behavior was modeled using a *Utility-Based System* that allows dynamic and adaptive decision-making based on statistics and environmental factors. This system evaluates various *Actions*, such as "work", "rest", "Supply", and other construction-specific activities, assigning a utility value to each based on the agent's statistics.
- **Hazard Model of the Entity**: Using the *Theory of Workspace*, *Hazard and Safety space*, a model was defined for each agent to manage the risks associated with its operations. This model includes:
    - **Safety Space**: A defined area where the agent can operate without risk of collisions or accidents. This space is determined based on the agents operational capabilities, the nature of the construction site, and surrounding activities.
    - **Hazard Space**: An area representing the limits within which an agent may encounter hazardous situations, such as collisions or hazardous interactions with other agents or site elements. This space identifies areas where increased attention or additional safety measures are required.

These integrated models allow for detailed and realistic simulation of construction site activities, providing a solid foundation for analyzing and optimizing construction operations. The following sections will detail the design choices, development, and functioning of each model.

1. Agent Physical Model

As described earlier, the first phase of agent creation involves selecting and developing a 3D model to represent the agent physically in the simulation environment. *Unity* offers a wide range of pre-animated characters that can easily be integrated into the project. In this context, given the focus on agent decision-making during construction tasks, it was decided to use simple 3D shapes to represent *Agents*. These shapes represent the agent's physical presence and are associated with the properties, characteristics, and physics functions of the *3D Dynamic Object* to simulate realistic movement dynamics and interactions within the game engine, as illustrated in Table 7.

AGENTS PHYSICAL MODEL			
Agent	**3D Model**	**Physical Properties**	**Behavior**
Worker	*Capsule*	*Mass, friction, resistance, speed*	*Movement, interaction with objects*
Truck	*Truck model*	*Mass, friction, resistance, speed*	*Movement along paths*

Table 8 - Agents physical characteristics

These *Agents* are equipped with specific *"Dimensional"*, *"Physics"*, and *"Identifying properties"*, as shown in Figure 29. The *"Agent Tag"* is coded with a unique identifier corresponding to the resources name in the task from the schedule. This allows for the subsequent identification, implementation, and instruction of the *Agent* in the simulation, according to the *"Task Properties"* of the *3D Static Objects* already managed by the *Activity Manager*. The information regarding the agent type, embedded within the *3D objects* as *Tags* allows for an organized management and dynamic loading of *Agents* in relation to the planned activities. To complete the *Agents* implementation, further behavioral and risk properties are incorporated into the *Agents* within the library, as detailed in the following Sections. This methodology simplifies the physical model of the *Agents* without compromising the ability to simulate realistic interactions and movement dynamics within the construction site.

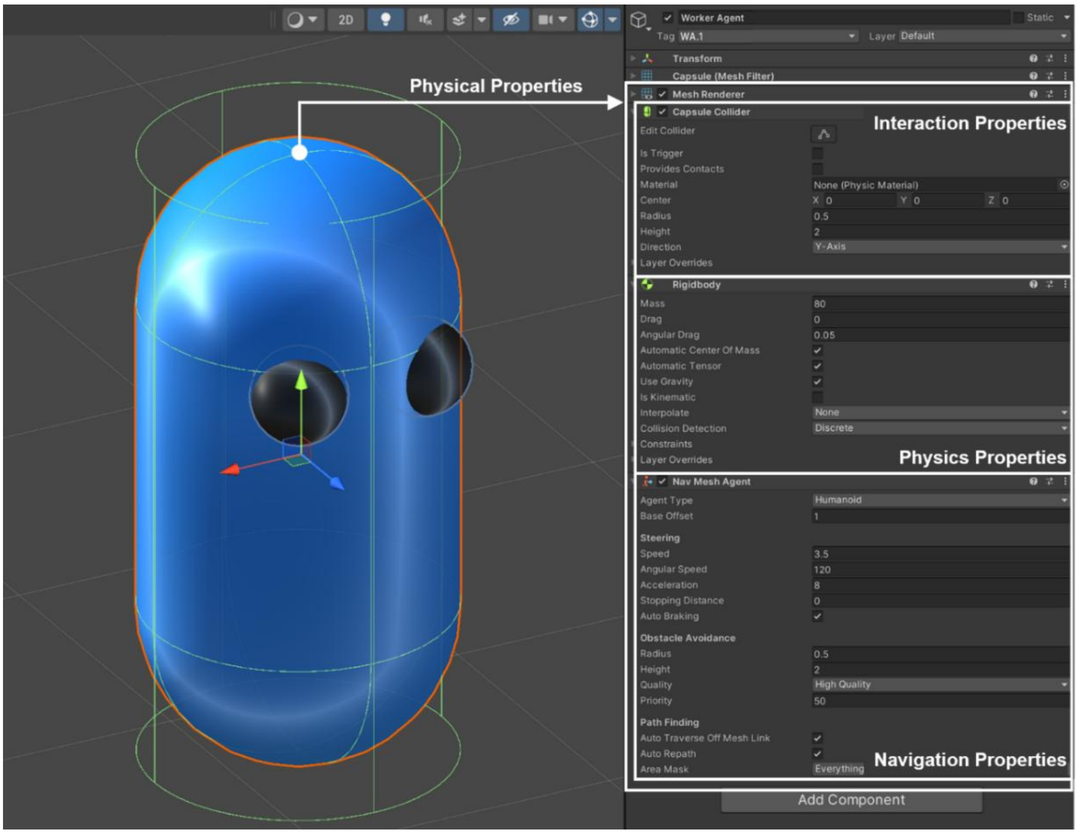


Figure 29 – Physical characteristics implemented like agents properties in the library.

Consequently, the research can focus on analyzing the events resulting from interactions between *Agents* and the environment, which is critical for evaluating work activities in complex environments such as construction sites.

2. *Agent behavior model*

As part of the creation of an *Agents Library* for construction scenario simulations, a behavioral model has been developed and implemented, allowing agents to autonomously make decisions about the actions they should take during work. The main goal of this system is to enable agents to make dynamic, adaptive decisions based on their internal state and the surrounding environment, ensuring a realistic and variable simulation with each execution. For this purpose, I applied a **Utility-Based System** to create the behavioral model for construction site agents. This system is particularly suited to simulating the behavior of both human workers and machinery in a dynamic and complex environment, such as a construction site. Although in this initial test, autonomous behavior for machines was not fully implemented, predefined paths and schedules were used for these agents (Figure 30).

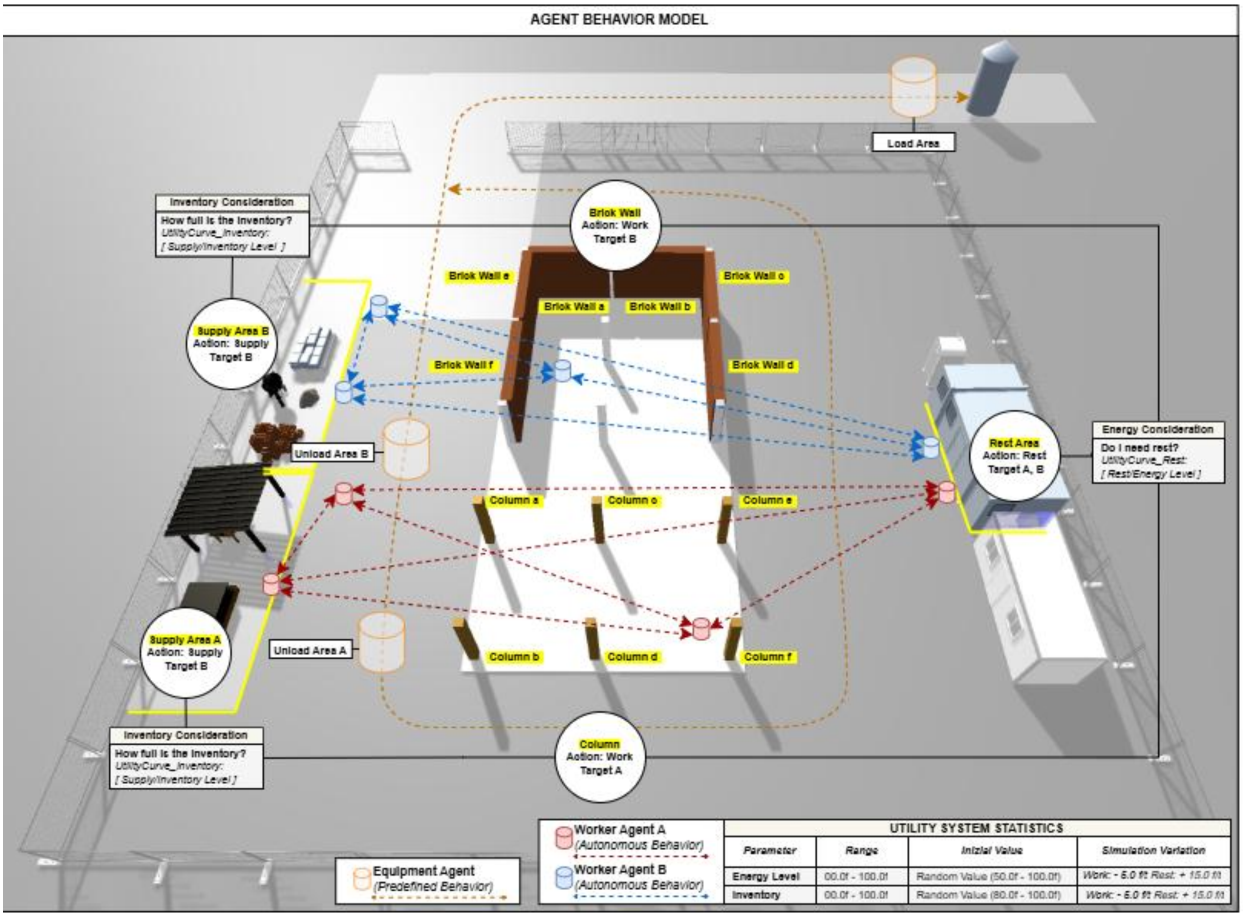


Figure 30 - Agent behavior model on a construction site proposed for the Test model of the system

The *Utility System* I developed allows agents to make adaptive decisions based on dynamic criteria, balancing the goal of completing tasks as efficiently as possible with the management of physical needs and available resources. For human workers, this means continuously evaluating the relative importance of various actions, such as working, resting, eating, or gathering materials, and responding promptly to changes in internal and external conditions. Using *"Utility Functions"*, agents can quickly adapt to variations in their environment and operational state, improving the overall outcome of the simulation. This approach ensures greater flexibility and responsiveness, which is essential for the efficient management of a construction site where conditions can change rapidly and unpredictably. Once an *Action* has been selected by the *Utility System*, I implemented a **Finite State Machine (FSM)** framework to handle the execution of that *Action* and the agent's movement within the simulation. The *FSM* determines whether the *Agent* is already at the correct location to carry out the task. If the agent is not yet at the destination, the *FSM* triggers the *"Navigation System"* to guide the agent toward the designated area. The movement and navigation of the agents are powered by the *"Navigation System"* provided by the Game-Engine, including features like *"Navigation Mesh (NavMesh)"* for pathfinding, the *"A* Algorithm*" for determining optimal routes, and *"Dynamic Obstacle Avoidance"* to navigate around moving objects and other agents. This ensures that *Agents* can traverse complex environments in a realistic manner, avoiding collisions while adapting to dynamic changes in the construction site, such as shifting machinery or temporary obstacles.

This separation of decision-making (handled by the *Utility System*) and action execution (managed by the *FSM* and *Navigation Systems*) ensures that agents are not only capable of choosing appropriate actions but also of carrying out those actions intelligently, accounting for environmental challenges. This two-part framework allows for seamless integration of task selection and movement, greatly enhancing the realism and overall fidelity of the simulation.

Methodology for the Utility-Based System: The development of a *Utility System* for simulating **Agents' Behavior** in a dynamic construction environment requires several key steps. These steps include defining parameters, creating utility functions, implementing the decision-making process, and integrating the system into the simulation environment. Below are the key points of this process:

- **Parameters, Actions, and Considerations**: The *Utility System* evaluates various *Actions* that an agent can take. In the construction site context, these actions represent specific tasks that either a human worker or a machine can undertake. The *Actions* are driven by the agents operational and physiological needs, the available resources, and the working conditions of the site. In this simulation model, *Actions* primarily involve moving the agent to the location where the action will occur and remaining there for the duration of the task. The Table 9 illustrates the *Actions* considered in the *Test Model*.

ACTION				
Action	Description	Target		Target Data Acquisition
		Agents A: WA.n	Agents: WB.n	
Work	*The worker moves to the work area to perform a task.*	*Columns ID:A.n*	*Brick Walls ID:B.n*	*3D Static Object Task Data*
Rest	*The worker moves to a resting area to recover energy.*	*Rest Area*		*3D Static Object Tag*
Supply	*The worker moves to the storage area for materials.*	*Supply Area A*	*Supply Area B*	*3D Static Object Tag*

Table 9 - Utility system action table, detailing action description, agent targets, and data acquisition methods for each action

Each *Action* is associated with specific *Considerations* that determine its Utility based on the agents' statistics parameters. The following table illustrates this relationship:

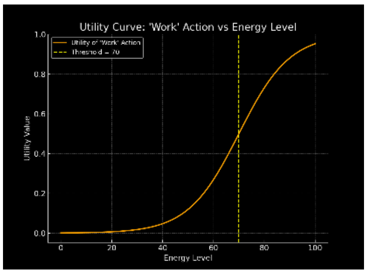
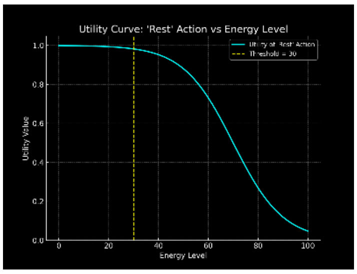
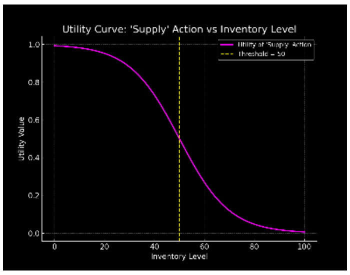
ACTION CONSIDERATION		
Action	Consideration	Statistics Involved
Work	*Primary Action*	*Energy Level*
Rest	*Do I need rest?*	
Supply	*How full is my inventory?*	*Inventory Level*
Utility Curve [Consideration/Statistics]		
Work / Energy Level	*Rest / Energy Level*	*Supply / Intenventory Level*
		
Utility_Work=1/(1+e^(-(Energy-70)/10))	Utility_Rest=1-Utility_Work	Utility_Supply=1/(1+e^((Inventory-50)/10))
Sigmoid function increases the utility of work at high energy levels, with 70 as the energy threshold, making work more effective only when the agent is sufficiently energized.	The inverse function indicates that rest becomes a priority when energy is low, with 30 as the threshold of increasing need for a break.	Sigmoid function increases the utility of resupply when inventory drops below the threshold of 50, prompting the agent to restock before resources are depleted.

Table 10 - Utility system table detailing the evaluation conditions considered and the statistics involved for each action

At the start of each simulation, the *Statistics Parameters* of agents are initialized with random values to ensure diversity in starting conditions. During the simulation, these parameters fluctuate over time based on actions taken and it are updated as the agent performs tasks:

STATISTICS			
Parameter	Range Value	Initialized Value	Simulation Variation
Energy Level	*00.0f – 100.0f*	*Random Value (50.0 – 100.0f)*	*Work: - 5.0 f/t* *Rest: + 15.0 f/t*
Inventory	*00.0f – 100.0f*	*Random Value (50.0 – 100.0f)*	*Work: - 20.0 f/t* *Rest: + 20.0 f/t*

Table 11 - Simulation parameter statistics table, detailing the range, initialized values, and variations during actions

To implement the described *Utility System* and *Finite State Machine (FSM)* framework within the construction simulation environment, a well-defined structure of scripts was developed. This architecture ensures that each component of the *Agents Behavior* (decision-making, movement, and task execution) functions cohesively, providing a robust foundation for realistic simulations. The System is divided into several core scripts, each responsible for handling a specific aspect of *Agents Behavior*.

The `WorkerAgentUtility Script` serves as the core of the decision-making process. This script manages the statistics of each agent, such as *"Energy Level"* and *"Inventory Level"*. These parameters are dynamically updated throughout the simulation, allowing the agent to continuously assess its current state. At the beginning of each simulation, the function `InitializeRandomParameters()` is called to randomly initialize the *Agents Statistics Parameters*, ensuring diversity in starting conditions and leading to varied

Agent behavior with each execution. The decision-making process is driven by the function `EvaluateActions()`, which assesses the available actions (*"Work", "Rest", "Supply"*) based on the Agent current Statistics and environmental conditions. The script calculates the desirability of each *Action* using predefined *Utility Functions* and their associated *Utility Curves*. Once all possible actions are evaluated, `DetermineBestAction()` selects the one with the highest utility. For instance, if an agent's energy is low, resting may have a higher utility value than working, prompting the agent to rest before resuming its task. This script is essential in managing the agents decision-making process by constantly assessing its needs and calculating the most optimal course of action (Table 10).

In addition to this, the `ActionManager.cs` script defines the individual actions that the agent can take, such as working, resting, eating, and gathering supplies. Each action is stored as a *Scriptable Object*, allowing flexibility and easy modification without altering the underlying code. The function `EvaluateUtility()` uses the agent's current parameters to calculate a utility value for each action, based on predefined utility curves (e.g., "Energy Level" vs. "Rest Action", hunger vs. eating utility). These curves, typically represented as *Response/Utility Curve* in *Unity*, allow for non-linear responses to the agents' statistics. For example, the utility curve for resting increases sharply as the agent's energy decreases, making rest more desirable when the agent is fatigued.

While the `WorkerAgentUtility Script` determines which action to perform, the `FSMController Script` is responsible for executing that action. This script implements a *Finite State Machine (FSM)* to manage state transitions between different tasks, such as moving, working, or resting. The function `CheckCurrentState()` continuously monitors the agent's state and determines whether a transition to a new state is required. For example, if the agent has chosen to *"Rest"* but is not yet at the designated rest area, the *FSM* will transition the agent into a "Move" state. Once the agent has arrived at the correct location, the function `ExecuteAction()` carries out the chosen task. In the case of resting, the agent remains in place for a defined period, recovering energy before transitioning to the next state.

Movement between locations is managed by the `NavigationSystem Script`, which leverages *Unity NavMesh* and *A* algorithm* for pathfinding. This script ensures that agents can navigate the construction site efficiently while avoiding obstacles, such as other agents or machinery. When the agent needs to move to a new location (e.g., *"work area", "rest area", "Supply Area"*), the `NavigateToTarget()` function calculates the most efficient route using the *NavMesh*, accounting for the dynamic nature of the environment. During movement, the script also handles real-time obstacle avoidance through the `AvoidObstacles()` function, allowing agents to dynamically adjust their path if a new obstacle, such as a moving vehicle or other workers, enters their route.

By separating decision-making and movement into different scripts, the system can handle both complex behaviors and real-time navigation within the construction site simulation. Here's an example of how these scripts work together:

1. The `WorkerAgentUtility Script` constantly monitors the agent's internal parameters and environment, evaluating possible actions and selecting the one with the highest utility.

2. Once an action is selected, the FSM in the `FSMController Script` ensures that the agent is in the correct location to perform the task. If the agent needs to move, it transitions to the “Move” state.
3. The `NavigationSystem Script` takes control, guiding the agent toward the target location using pathfinding and dynamic obstacle avoidance.
4. Upon arrival, the *FSM* transitions the agent to the correct state (e.g., *“Work”, “Rest”, “Supply”*), and the action is executed via `ExecuteAction()`.
5. The `ActionManager Script` monitors the progress of the task and, upon completion, triggers the next evaluation cycle in the `WorkerAgentUtility Script`.

This modular design allows for flexibility, scalability, and realistic behavior, making it well-suited for complex construction site simulations where agents must dynamically adapt to changing conditions. By separating decision-making, movement, and task execution into distinct scripts, the system can handle a wide range of agent behaviors and scenarios with high fidelity

3. Hazardous representation

During the planning phase of a construction site, it is essential to recognize that interactions between various categories of site entities can lead to hazardous situations. These interactions are often influenced by factors such as strategic placement, spatial distribution, sequencing of operations, and the types of entities involved. Frequently, these dynamics result in collisions which, depending on the entities involved, can pose significant safety risks for workers (Figure 32). In the context of Building Information Modeling (BIM), modeling the interactions between construction activities and related hazardous events remains an unresolved issue, despite the numerous solutions that have been proposed. A common approach involves representing the site's usable space, referred to as *"Work Spaces"*, through parametric objects enriched with non-geometric information. However, these representations often fall short in capturing the dynamic nature of construction site interactions. For this study, the objective is to identify potential interference and collision scenarios between workers and equipment using the dynamic workspace management model developed by Getuli et al. (2018), titled *"Computational workspaces management: a workflow to integrate workspaces dynamic planning with 4D BIM."* This approach uses specific volumes to define *Hazardous Spaces* that indicate potential collisions for each agent within the test model. These Hazard Space are described as follows:

- **Hazard Space**: These spaces are delineated by specific containment volumes, which serve as virtual monitoring zones around the agent. The so-called "Hazard Space" represents the necessary buffer to prevent collisions with other entities or agents. This safety space is defined by a bounding volume that envelops the agent, tailored according to the agent’s physical characteristics and movement. This volume assists not only in monitoring and managing interactions between agents or between agents and other elements of the model, but it also records these interactions, particularly collisions, that occur during the simulation. The analysis of these collisions provides critical data regarding the likelihood of hazardous events (Figure 31).
- In the test model, the *Hazard Spaces* for both the truck and the worker were modeled using an additional component, *Box Collider*, with simple geometric shapes to represent the *Hazard Spaces*

around the agents. This choice was made considering the basic characteristics of the agents in the current *Test Model*. However, nothing prevents the use of more complex shapes in future implementations. By employing more advanced geometry, it would be possible to create volumes that more accurately reflect the specific hazards associated with each resource. This would allow for a more precise representation of the physical and operational risks posed by different site entities, enhancing the accuracy of collision detection and risk analysis (Figure 31).

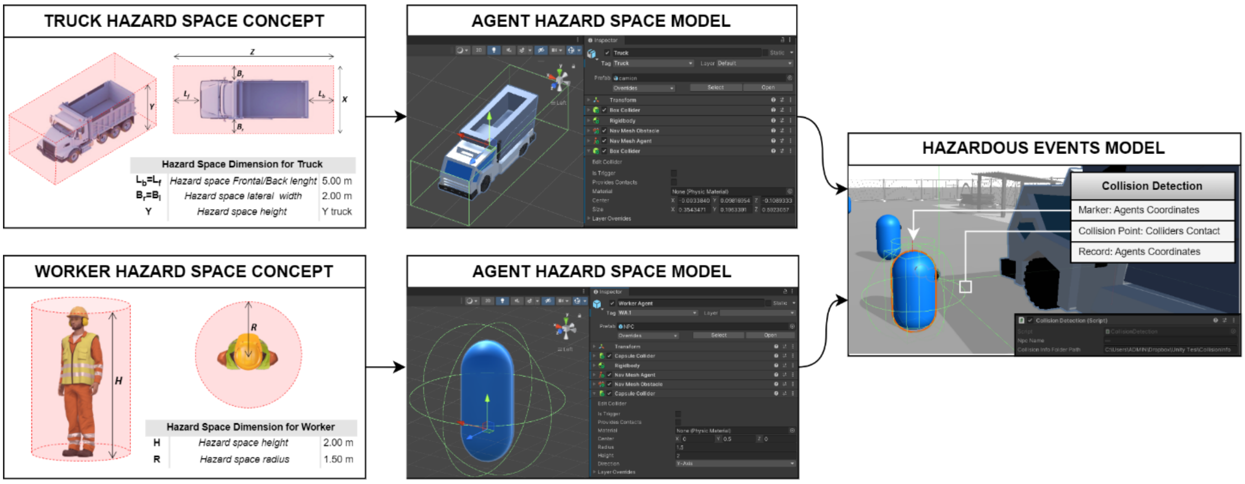


Figure 31 - Hazard space model for site agents

Based on the design and planning of the construction site, and considering the resources involved in the operations of the test model, it becomes evident that *Hazardous Events* resulting from various types of collisions are likely to occur. For example, collisions between a worker and equipment can result in "*Struck-by*" or *"Run-Over" Hazards*, while collisions between workers from different teams can lead to a range of risks depending on the activities being performed. Given that this is an initial implementation of the proposed system using a simplified test model, the analysis has been limited to collisions between two types of *Dynamic Object*: workers and equipment (Figure 32).

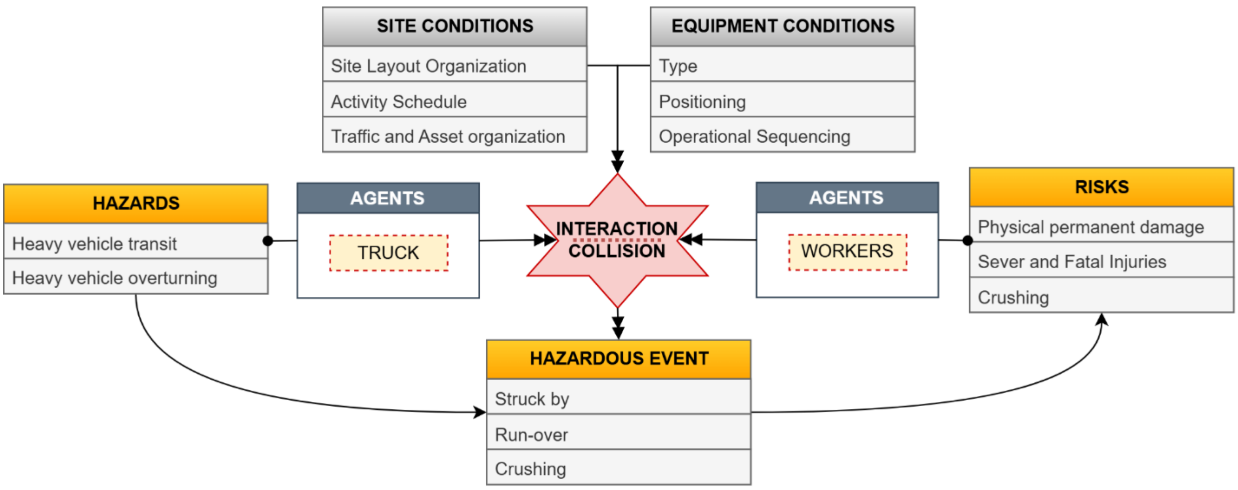


Figure 32 - Diagram of interactions and collisions between site agents, highlighting how site and equipment conditions influence hazards and risks

However, with a complete library of *3D Construction Agents*, accurately modeled in terms of *Behavior* and *Hazard Spaces*, the method can be extended to capture a broader range of collision scenarios that pose risks to health and safety due to interference among various site resources.

A detailed analysis of the recorded collisions during the simulation is essential for identifying and quantifying potential hazardous events related to collisions on the construction site. Through this methodology, it is possible not only to detect and document actual collisions but also to estimate the likelihood of *hazardous Events* arising from these interactions. This process supports the prediction and implementation of preventive measures, helping to improve the design and planning of the site and operations to mitigate collision risks.

Ultimately, integrating collision analysis into the BIM model significantly enhances on-site safety management by providing a predictive approach that validates design and operational decisions aimed at preventing hazardous events. This methodology represents a vital step in advancing the safety management of construction sites, particularly in reducing risks posed by dynamic interactions among workers, equipment, and other site resources.

Agent data implementation

In the proposed system, the instantiation of Agents occurs at the start of the simulation by utilizing the *"Task Properties"* data that had been previously transferred to each component involved in construction activities. Upon initiating the simulation, the `Orchestrator Script`, which manages the sequencing of *Static Objects* in relation to the timeline and duration of tasks, handles the instantiation of agents within the simulation.

After defining the library of available agents and acquiring the scheduling and planning data for construction activities, the advanced simulation system is fully capable of 1) instantiating agents and 2) applying the corresponding operational instructions, such as task objects, sequences, and durations. These instructions are executed when the simulation begins.

At the beginning of the simulation, the system checks the elements present in the model and identifies the *"Task Properties"* associated with the agents. It then uses this information to instantiate the appropriate type and number of agents as required (Section [6.2.4.1]). These agents are placed at specific locations on the construction site, with positions chosen based on an analysis of site access and transit procedures. In this instance, the instantiation occurs near designated storage areas.

Once the instantiation process identifies the agents to be deployed, a parallel process activates the `AgentBehavior Script`. This script analyzes the *"Task Properties"* related to the Gantt scenario and transfers the operational instructions to the agent, reconstructing the specific construction plan within its *Inspector*. This process involves several steps:

- Identification of the elements involved in the activity, providing details about the location of *Action Target* in relation to the agent's behavior;
- Definition of the order and sequence of objects, organizing the agents' tasks according to the chronological order of the planned activities;
- Association of the activity's duration properties, specifying the total time allocated for the *Actions*.

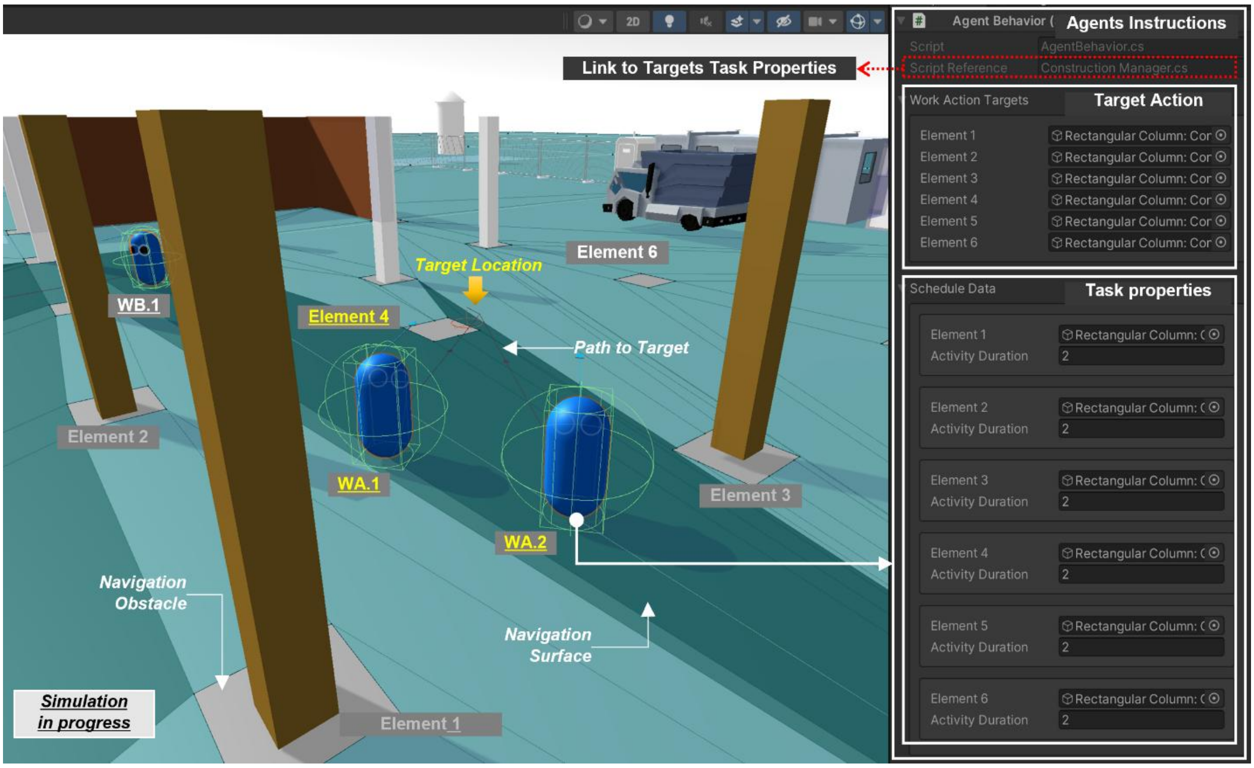


Figure 33 - Visualization of Task Properties transferred as agents' instructions (target, sequence, and duration) when instantiated during the simulation.

The information regarding the construction sequence and duration of each agent's activities is accessible during the simulation through properties displayed in the agent's Inspector. This information is utilized both by the `AgentBehavior Script`, to guide target actions, and by the `Orchestrator Script`, to manage the agent's task duration.

6.2.4 Simulation Scene

The *Simulation Scene* serves as the core operational component of the Agent-Based Simulation System developed for this project. In this scene, all configurations and parameters defined during the setup phase are executed to simulate real-time construction site dynamics. Once the model is loaded and the agents are configured, the simulation begins within the *Simulation Scene*. At this stage, the system performs a series of iterations representing various construction site activities over time, as programmed in the 4D BIM model. The agents move, interact with each other, and engage with the environment, carrying out the scheduled tasks according to predefined behavioral rules. These simulations can be controlled in real time, allowing users to observe and analyze the evolution of construction site operations.

To achieve this, a dedicated Game-Object named *Simulation Management* was implemented, equipped with a component containing a function called `Orchestrator Script`, responsible for two primary tasks: (1) initiating and executing the simulation based on the project schedule and 4D BIM data (Section [6.2.4.1]) , and (2) logging collisions, as detailed in the following sections (Section [6.2.4.2]).

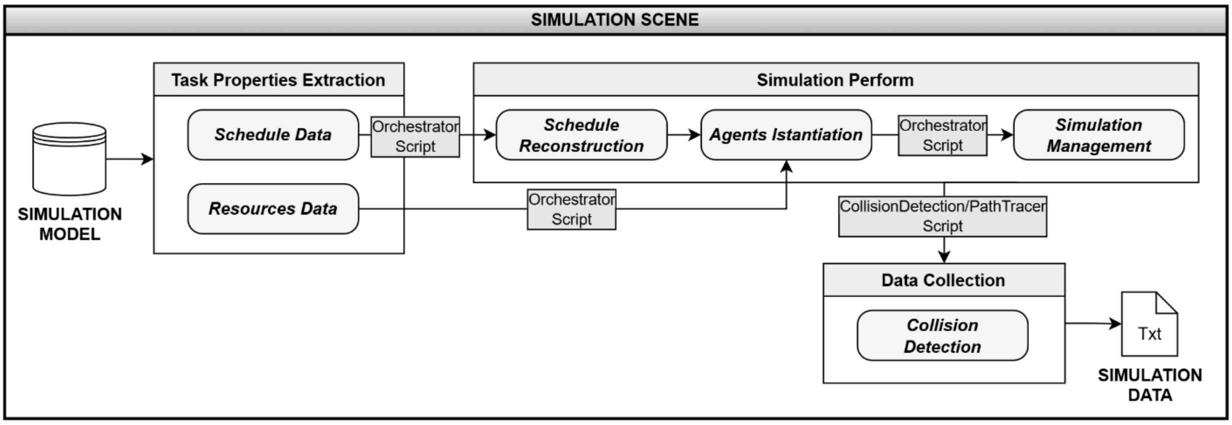


Figure 34 - Overview of the Simulation Scene Workflow, where configurations and parameters are executed to simulate real-time construction dynamics

6.2.4.1 Simulation performs

The primary function of the `Orchestrator Script` is to manage dynamic interactions between *Static and Dynamic Objects*, ensuring they are activated and controlled according to the project's 4D BIM schedule. By leveraging the *"TaskProperties"* data pre-configured for each entity, including *"Start/End dates"* and *"Duration"* of activities and *"Number, Name, RBS of agents"*, the `Orchestrator Script` handles the instantiation of *Static Object* and *Agents* (such as workers or trucks) at the correct times and locations. This ensures synchronization between the simulation environment and the construction timeline.

A custom script, known as the *`Orchestrator Script`*, was developed to manage the visibility of static entities, instantiate and remove agents based on task properties, and control entities within the simulation timeline. The script follows these key steps:

1. **Initialization of Entities and Tasks**: At the start of the simulation (within the `Start()` method), the `Orchestrator Script` identifies all entities in the *Scene* that contain the *"TaskProperties"* component. It retrieves essential data, such as the *"Start Date", "End Date", "Duration", "Number of agents", "Agent Type"*, and other relevant properties. Using this information, the *`Orchestrator Script`* creates and manages a series of tasks, which are stored in a `taskQueue`. This queue is then used to control when objects should be activated, agents instantiated, and when the cleanup process should begin once tasks are completed.
2. **Simulation Time Management**: Throughout the simulation, the *`Orchestrator Script`* continuously updates the simulation time variable. This time is calculated using Unity `Time.deltaTime()`, which measures the time between frames, and is scaled by a `TimeScaleFactor()`. This allows for adjusting the speed of the simulation according to the user's needs. The `UpdateSimulationTime()` method ensures that the current simulation time is continuously checked against the *"Start Date"* and *"End Date"* for each task to determine when tasks should start or stop.
3. **Task Management**: For each task, the `Orchestrator Script` checks whether the simulation time has reached the task's *"Start Date"*. When this occurs, the following actions are taken:
   - *Static Objects* associated with the task are activated and remain visible for the duration of the task.

- *Agents* (such as workers or trucks) are instantiated if required by the task. The *"TaskProperties"* component specifies the number and type of *Agents* needed, ensuring the correct *Dynamic Object* are deployed at the correct time.

4. **Dynamic Loading of Agent Prefabs**: When an *Agent* needs to be instantiated, the `Orchestrator Script` uses the *"Resources Name"* specified in the *"TaskProperties"* (e.g., "WA.1" or "T.1"). This value corresponds to an *"Agents Prefab Tag"* stored in *Unity Resources folder*. The Script utilizes the `Resources.Load<Game-Object>()` method to dynamically load the appropriate prefab at runtime. For instance, if the task specifies resources (*"WA.1", "T.1"*), the script will load and instantiate the corresponding prefab with the same *Tag* value from the *"Resources folder"* at the correct time during the simulation.
5. **Managing Agents**: For tasks requiring agents, the `InstantiateAgents()` method reads the number of agents number from the *"TaskProperties"* component. This value determines how many agents are instantiated at the designated location within the scene. The agents are instantiated in a loop, ensuring that the correct number appears at the proper location in the simulation. Once the task reaches its *"End Date"*, the `RemoveAgents()` method is called to remove the agents instantiated for that task. This cleanup ensures the simulation remains efficient and that agents are removed once their tasks are completed.
6. **Managing Static Entities**: *Static Objects*, such as construction components, are handled differently from agents. Once a static object is activated at the task start, it remains visible even after the task is completed. This is because static objects typically represent permanent structures on-site that continue to exist as the project progresses. The `Orchestrator` ensures that static entities remain visible according to the project timeline and stay active after their associated tasks have finished.
7. **Real-Time Interaction and Time Scaling**: The `Orchestrator` allows for real-time interaction during the simulation. The time scale factor can be adjusted to either speed up or slow down the simulation, enabling users to observe specific events in detail or fast-forward through less critical phases. Both *Agent Behaviors* and task sequences remain synchronized with the simulation timeline, ensuring events occur in the correct order and at the right times, as specified in the 4D BIM schedule.

Adding a dedicated Game-Object titled *"Simulation Management"* allows the implementation of the `Orchestrator`, which seamlessly coordinates the various simulation elements while providing real-time interaction and control over the flow of construction activities through the ability to adjust simulation speed via the Inspector.

6.2.4.2 Data collection

During the simulation, the system continuously monitors the *Agent Behavior* and records detailed data on their performance throughout the different construction phases. Critical events, such as collisions between agents and static objects or other agents, are logged as potential incidents or interferences on the construction site, as described in Section [6.2.3.2]. This approach allows for predictive Risk Assessments associated with different site configurations and worker safety. The system includes a custom `CollisionDetection Script`, which monitors interactions between agents during the simulation. Each

Agent is equipped with this script, and whenever a collision occurs, the collision data is collected and logged into a text file, created in a user-specified folder. This process operates as follows:

1. **Agent Identification and Log File Creation**: Each agent has a unique identifier (*"Name", "Tag"*) and a designated folder (`collisionInfoFolderPath`) for storing collision data. At the start of the simulation, a unique log file is generated using a timestamp (`yyyyMMdd_HHmmss`) to mark the beginning of the simulation. This log file is created in the folder specified by the user.
2. **Collision Detection and Data Logging**: When two agents collide, the script detects the event using the `OnTriggerEnter` method. If the other *Agent* involved in the collision is another *Agent*, the following details are logged:
   - Identifiers of the agents involved in the collision.
   - The type of collision (e.g., *"worker/truck", "truck/truck", "worker/worker"*).
   - Coordinates of the collision point (*"CollisionPoint.x", "CollisionPoint.y", "CollisionPoint.z"*).
   - The *"Speed"* of the agents involved.
3. **Collision Data Storage**: The *"Collision Data"* are stored in a dictionary associated with the agent's name, accumulating all the collisions detected during the simulation.
4. **Temporary Collision Visualization**: For each detected collision, a temporary red marker (`Debug.DrawRay`) is drawn at the collision point for a specified duration (`markerDuration`), allowing quick visualization of the event in the scene.
5. **Writing Data at Simulation End**: At the end, cumulated collision data is written to two formats:
   - **Agent-Specific Files**: For each *Agent*, a separate log file is created that contains all collisions involving that agent, using the format *"AgentName_CollisionInfo_yyyyMMdd_HHmmss.txt".*
   - **General Simulation File**: A general log file, titled *"CollisionInfo_yyyyMMdd_HHmmss.txt",* records all collisions detected during the simulation, providing an overview of the entire process.

In addition, each agent is equipped with a `PathTracer Script` to record the agent's movement paths during the simulation, following these steps:

1. **Line Renderer Configuration**: At the script start, the presence of a `LineRenderer` component on the associated object is verified. If the component is absent, it is added. The `LineRenderer` is configured to draw a continuous line representing the agent path, with the specified color and width.
2. **Output File Creation**: A text file (*AgentName_path.txt*) is created in the user-specified output folder. This file will contain the coordinates of the agent movement points.
3. **Adding Current Position**: At each interval defined by `timeStep`, the agent current position (`transform.position`) is added to a list of points (`pathPoints`), accumulating all positions traveled during the simulation.
4. **Line Renderer Update**: The `LineRenderer` is updated to include all the points in the list, drawing a continuous line representing the agent's completed path.
5. **Writing Coordinates to Output File**: Each time a new point is added to the list, the coordinates (*x, y, z*) of the current position are written to the text file (*path.txt*). These coordinates are formatted as strings and recorded sequentially, creating a chronological record of the agent's movement throughout the simulation.

6. **Closing the Output File**: When the object to which the script is attached is destroyed, the output file is properly closed to ensure that all recorded data is permanently saved.

The *Simulation Scene* provides users with several controls to manage the execution of the simulation. Users can start, pause, or stop the simulation, as well as adjust the simulation speed to observe specific events in greater detail or accelerate the process to view the overall results more quickly. Additionally, users can modify simulation parameters, particularly those controlling agent behavior, to run multiple simulations with different variables and compare the results. The log files generated during the simulation, including collision logs and path traces, are essential for post-simulation analysis. They provide precise details regarding collisions and agent movement paths, allowing users to identify critical situations resulting from poor construction site design or inefficient activity planning. By analyzing these data, researchers can gain a comprehensive understanding of agent behavior within the construction environment and identify areas of concern that could lead to hazardous conditions.

6.2.5 Visualization Scene

The *Visualization Scene* represents the final phase of the developed Agent-Based Simulation system. In this stage, the collision data recorded during previous simulations is utilized to generate a three-dimensional risk map. After selecting the appropriate *"Collision Data File"* through the user interface in the *Inspector*, the user can activate the system to calculate risk values associated with hazardous events, specifically, agents' collisions. The system has been developed to calculate risk following the standards outlined in the relevant *UNI EN ISO Guidelines for Risk Management*.

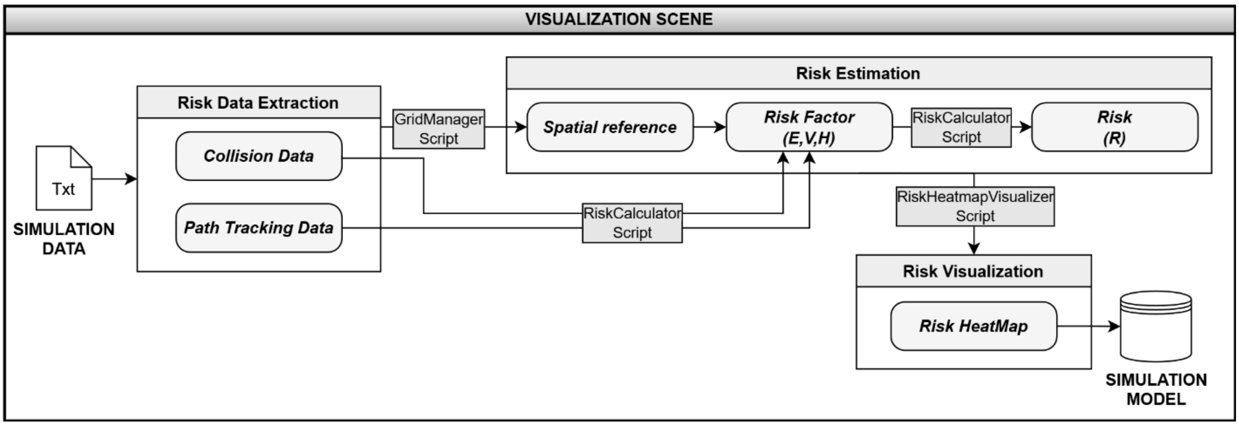


Figure 35 - Diagram of the Visualization Scene, illustrating the process of risk extraction, estimation, and visualization

The calculated risk values and corresponding heatmaps are derived from three fundamental factors: *Vulnerability (V)* (severity of the incident), *Exposure (E)* (frequency of agent movement across specific areas), and *Likelihood (H)* (likelihood of collisions). Using specialized algorithms, the system calculates these values based on the recorded collision data. The final output is visualized as a heatmap applied directly onto the horizontal surfaces of the 3D BIM model, allowing users to visually identify high-risk areas. Horizontal surfaces in the model are color-coded: low-risk zones are shown in shades of green, transitioning through yellow and orange for intermediate risks, and finally red for areas with the highest risk values. This visual representation allows for immediate and intuitive analysis of risk distribution within the construction site, supporting preventive analysis, operational decisions, and improvements in safety management. The Visualization Scene implements this process through three core scripts:

1. `GridManager`: This script creates a spatial grid on the horizontal plane of the model.
2. `RiskCalculator`: It processes the *Collision Data* (in *.txt* files) to calculate the *H, V,* and *E* factors for each cell in the grid, generating a *Risk Map*.
3. `RiskHeatmapVisualizer`: This script visualizes the *Risk Heatmap* values by applying color to the horizontal surfaces of the 3D model based on the calculated Risk levels.

The following sections provide a detailed explanation of the functionality of the scene, the organization of the risk calculation process, and the visualization of the risk. It describes how collision data is processed and how the 3D heatmap is generated.

6.2.5.1 Risk estimation

To assess and visualize risk concerning the spatial location of *Hazardous Events*, the system implements the *Risk Estimation* process in two phases:

1. **Creation of a Spatial Reference in the Model**: When the visualization scene is initiated, the system divides the horizontal planes where collisions occur into a two-dimensional grid (*X* and *Y axes*), where each cell has dimensions specified by the user. The `GridManager Script`, which activates upon scene startup, generates this grid, which serves as a spatial reference for risk calculation and heatmap visualization. The steps in this process are as follows:
   - **Grid Creation**: Each cell is represented by a central position, calculated using the coordinates (*x * cellSize, 0, z * cellSize*), where x and z are the grid indices.
   - **Storing Cell Coordinates**: The script stores the coordinates of each cell in an array called `gridCells`, which is used to map collision events and agent movements to specific areas of the model. The grid enables:
     - **Associating hazardous events with specific zones:** Instead of treating the construction site as a single area and assessing risk globally, dividing the site into cells allows for localized risk analysis. This granularity helps pinpoint high-risk areas more precisely.
     - **Calculating risk factors for localized areas:** The three risk factors (*H, V,* and *E*) depend on what happens in each specific cell. By using a grid, risk can be calculated separately for each area, making the analysis more accurate and reflective of the actual distribution of events on the site.
     - **Visualizing the grid:** The grid facilitates risk visualization as a heatmap. By dividing the plane into cells, each cell can be colored based on the calculated risk, creating a visual map that highlights high-risk areas.
     - **Managing data in an organized and scalable way:** Instead of tracking every single collision or movement individually, the system accumulates data for each cell. This method simplifies calculations and reduces computational complexity.
2. **Risk Calculation Relative to the Spatial Reference**: The risk calculation in the system is based on three main factors: *Likelihood (H), Vulnerability (V),* and *Exposure (E)*. These factors are combined to determine the overall risk in each area of the construction site, divided into grid cells. The

`RiskCalculator Script` manages this process by reading the collision data and agent paths from the .txt files generated during the simulation. The total risk value for each grid cell is calculated using the following formula: $\boldsymbol{R = H\ x\ V\ x\ E}$

The `RiskCalculator Script` uses three primary functions to determine each factor:

1. **`CalculateLikelihood()`**:
   This function calculates the *Hazard Likelihood (H)* of a collision based on the number of collisions recorded in a specific grid cell. The collision density is normalized relative to the maximum number of collisions observed across all cells in the simulation area. This means that each cell collision count is expressed as a percentage of the maximum observed value, providing a standardized comparison. Cells with a higher number of collisions have a higher value of *H*, which is normalized on a scale of 1 to 5.

LIKELIHOOD [H]		
Range	**Description**	**H Score**
0% - 20%	*Low*	*H = 1*
21% – 40%	*Medium/low*	*H = 2*
41% - 60%	*Medium*	*H = 3*
61% - 80%	*Medium/High*	*H = 4*
81% - 100%	*High*	*H = 5*

Table 12 - Calculation and scoring system for the Likelihood of occurrence of the hazardous event based on the percentage of collisions detected in a cell

2. **`CalculateVulnerability()`**:
   Vulnerability (V) is determined based on two key parameters ():
   - **Type of Collision**: Collisions involving heavy machinery or heavy machinery and workers are considered more severe than those between workers, due to the increased risk of injury.
   - **Agent Speed**: The *"Speed"* of agents at the time of collision also affects the severity of the event. Higher-speed collisions are considered more dangerous. The *"Speed"* of agents is normalized against the system's maximum recorded speed.

   The final *V* value is determined by combining these two factors, normalized on a scale of 1 to 5:

VULNERABILITY [V]		
Type	**Description**	V_{Type}
worker/worker	*Low*	*V = 1*
worker/machinery	*Medium*	*V = 2*
machinery/machinery	*High*	*V = 3*
Speed	**Description**	V_{Speed}
< 2.5 m/s	*Low*	*V = 1*
2.5 – 5 m/s	*Medium*	*V = 2*
> 5 m/s	*High*	*V = 3*
Range [V_{Type} + V_{Speed}]	**Description**	**V Score**
2 - 3	*Low*	*V = 1*
4 – 5	*Medium/low*	*V = 2*
6 – 7	*Medium*	*V = 3*
8 – 9	*Medium/High*	*V = 4*
10	*High*	*V = 5*

Table 13 - Calculation and scoring system for Exposure, based on the frequency of agent movements detected in a cell

3. **`CalculateExposure()`**:

Exposure (E) is calculated based on the frequency of agent movement through a given grid cell counting the steps in each cell of the grid. This value is normalized against the maximum number of agent movements observed across all cells. Cells with higher agent traffic receive a higher *E* value, normalized on a scale of 1 to 5.

EXPOSURE [E]		
Range	Description	E Score
0% - 20%	*Low*	*E = 1*
21% – 40%	*Medium/low*	*E = 2*
41% - 60%	*Medium*	*E = 3*
61% - 80%	*Medium/High*	*E = 4*
81% - 100%	*High*	*E = 5*

Table 14 - Calculation and scoring system for Exposure, based on the frequency of agent movements detected in a cell

Through this detailed grid-based approach, the system ensures that the calculation of risk factors such as *Hazard Likelihood (H), Vulnerability (V),* and *Exposure (E)* is both spatially precise and tailored to the localized dynamics of the construction site. By assigning these values to individual cells, the method enables a granular evaluation of risk, allowing for targeted analysis of high-risk zones and supporting the subsequent generation of accurate risk heatmaps. The overall *Risk (R)* in each cell is calculated by multiplying these three factors, with results categorized according to the risk scoring table.

RISK [R]		
Range [H x V x E]	Description	R Score
1 - 10	*Low*	*R = 1*
11 - 20	*Medium/low*	*R = 2*
21 - 40	*Medium*	*R = 3*
41 - 80	*Medium/High*	*R = 4*
81 - 125	*High*	*R = 5*

Table 15 - Calculation and scoring system for Risk

This table ranges from 1 (Very Low) to 5 (Very High) and provides a structured assessment of potential hazards in each area. By mapping these risk levels across the site, the system enables proactive identification and management of zones requiring heightened safety measures.

6.2.5.2 Risk Heatmap visualization

Risk visualization is performed using a 3D heatmap, which applies colors to the BIM model's surfaces according to the calculated risk values in each grid cell. The `RiskHeatmap3DVisualizer Script` handles the generation of the heatmap using the risk data calculated by the `RiskCalculator`. The system colors the horizontal surfaces of the 3D model based on the overall *Risk Level*, providing a clear visual representation of high- and low-risk areas on the construction site.

The `RiskHeatmapVisualizer script` includes several functions to map risk values to a visual representation through gradient colors. The main stages of the process are:

1. **3D Heatmap Generation**: The `GenerateHeatmap3D()` function analyzes each surface of the 3D model, mapping it to a corresponding grid cell. The risk value of that cell, previously calculated and stored in the risk map (`riskMap`), is retrieved and normalized on a scale from 0 to 1. This normalized value is then used to determine the color applied to the surface.
2. **Risk Color Calculation**: The `CalculateRiskColor()` function generates a color for the surface based on the normalized risk value. The heatmap uses a color scale from green (low risk) to yellow/orange (medium risk) to red (high risk):

RISK [R]		
R Score	**Description**	**Color**
0 - 1	*Low*	*R = 1*
1 - 2	*Medium/low*	*R = 2*
2 - 3	*Medium*	*R = 3*
3 - 4	*Medium/High*	*R = 4*
4 - 5	*High*	*R = 5*

Table 16 - Calculation and scoring system for Risk

3. **Applying the Material to the Surface**: After calculating the risk color, the script creates a new material by copying the base `heatmapMaterial` and modifies its color to reflect the calculated risk. The updated material is then applied to the corresponding surface of the 3D model, effectively displaying the heatmap directly on the model.

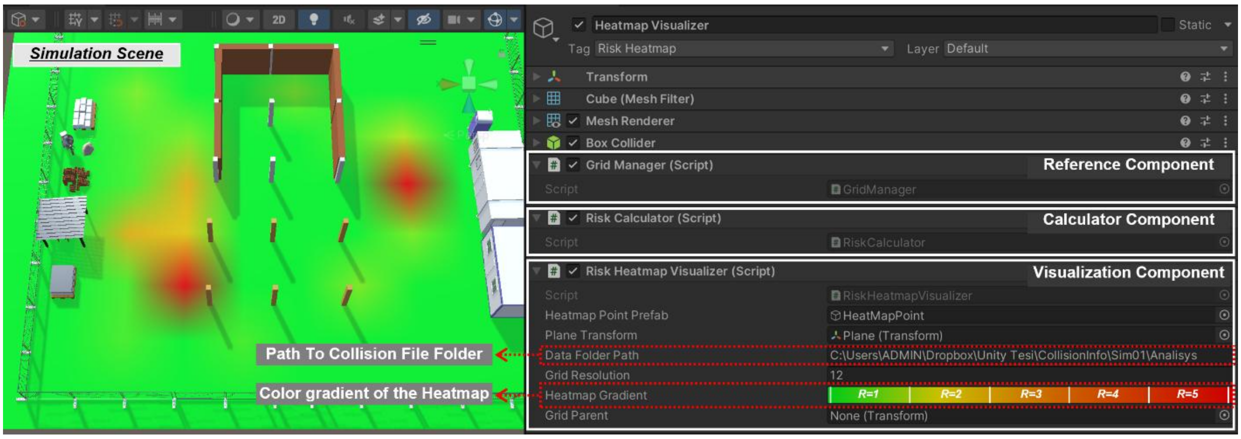


Figure 36 - Risk heatmap visualization within the Simulation Scene, featuring dedicated components for risk data management, calculation, and display

The generated heatmap provides an intuitive representation of the distributed risk across various areas of the construction site. Safe zones, characterized by low-risk values, are easily identifiable through shades of green. Areas of medium risk are colored yellow or orange, depending on the risk level, while high-risk zones are highlighted in red. This visual representation offers a critical tool for risk analysis and safety management on-site, enabling users to quickly identify areas requiring intervention or preventive measures.

By integrating the risk data into a visual form, the heatmap allows stakeholders to assess the spatial distribution of potential hazards effectively. This aids decision-makers in improving the safety planning process, ensuring that high-risk areas are addressed proactively to prevent accidents. The risk heatmap is a vital element of the system, bridging the gap between raw collision data and actionable insights for enhancing on-site safety

6.3 Results and decision support for safety measures

The test model was designed to evaluate the effectiveness of an advanced simulation system capable of identifying and quantifying struck by and vehicle impact risks in this specific test, involving heavy vehicle transit within a controlled and predefined construction environment. While the physical layout of the site remained constant across simulations, agent behavior varied according to dynamic operational parameters such as energy, inventory, and activity status. This approach allowed us to observe how variations in agent behavior influence exposure to the risks in specific areas of the site, simulating potential hazard scenarios that may arise in real-life construction settings.

The primary objective of the simulation system was to assess its ability to detect known hazard situations, such as dangerous interactions between heavy vehicles and workers. Through utility-based behavioral modeling and autonomous agent decision-making, the system dynamically responded to environmental stimuli, creating realistic interference scenarios. The system calculated risk values based on *Likelihood of occurrence (H), Vulnerability (V),* and *Exposure (E)*, using the *UNI EN ISO Risk Assessment Model*. This validated the methodological approach for identifying and visualizing struck by and impact risks for workers. The heatmaps generated during the simulations clearly highlight high-risk areas, particularly in the heavy vehicle transit zones where overlap with pedestrian paths frequently occurs. These results demonstrate the system's capability to detect risk situations and represent them graphically, facilitating an immediate understanding of critical areas for safety managers.

The heatmaps (Table 17) indicate that high-risk areas are concentrated near intersections between vehicle paths and work zones, pinpointing where contact likelihood is highest. This confirms the validity of the system's approach in automatically identifying critical aspects of the site layout, providing both quantitative and visual data essential for safety planning. The heatmaps generated from the simulations provide a visual representation of high-risk areas within the construction site, using a color scale to differentiate varying hazard levels. The most intense colors (red) signify higher risk levels, where struck by or impact are more likely to occur. For example, in Table 17, Risk Heatmap 1, 2, and 3, hot spots are highlighted primarily along the pathways of heavy machinery, where agent movement intersects pedestrian routes. These visual results confirm that the simulation system can accurately identify and quantify risk zones, offering safety managers a clear indication of areas that require intervention. Additionally, the ability to visualize risk through heatmaps simplifies data interpretation, allowing decision-makers to intuitively understand high-risk zones without requiring extensive data analysis. This graphical representation enables rapid diagnosis of danger areas, facilitating quicker identification of critical issues and thus supporting a more informed and timely decision-making process.

To obtain a comprehensive risk assessment, four groups of simulations were conducted, each consisting of ten iterations of the same scenario. In each iteration, agents autonomously made decisions based on a *Utility System* and a *Finite State Machine (FSM)* model to navigate the site. This approach enabled detailed data collection and allowed for the calculation of an aggregate risk for each group, reliably representing the average risk pattern across multiple scenarios. By combining the results of all groups, a more stable and holistic representation of struck by and impact risk was obtained, which is useful for evaluating the overall effectiveness of safety measures.

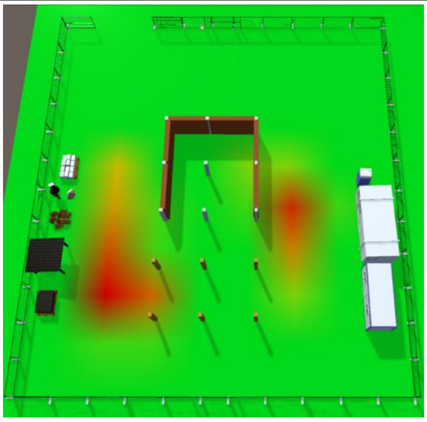
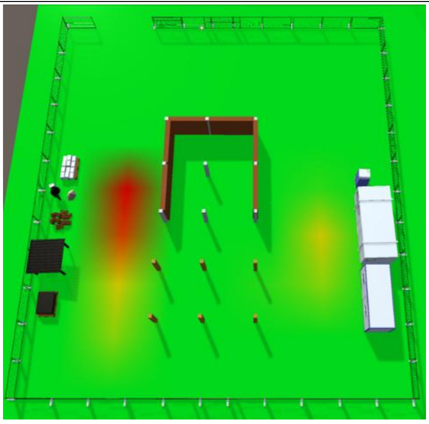
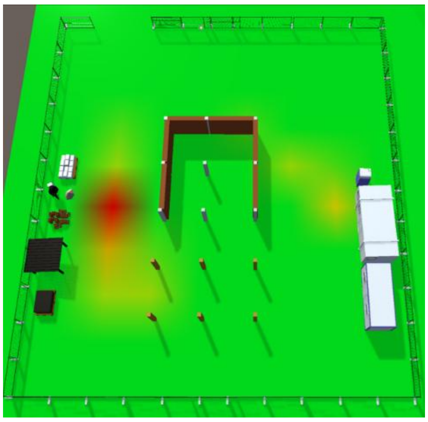
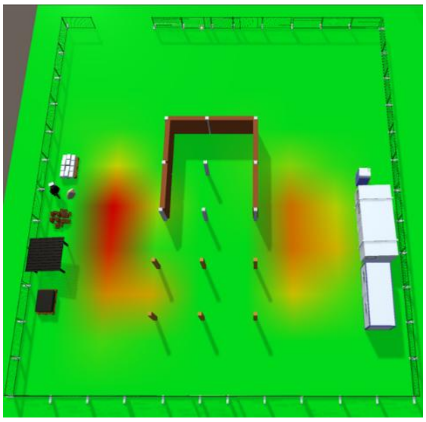
RISK HEATMAP			
Risk Heatmap 1		Risk Heatmap 2	
Simulated Risk Level - Group 1		Simulated Risk Level - Group 1	
			
Agent Set 1		*Agent Set 2*	
Initial Inventory Level	*50-70 range (Random)*	*Initial Inventory Level*	*50-100 range (Random)*
Initial Energy Level	*60 – 80 range (Random)*	*Initial Energy Level*	*70 – 90 range (Random)*
Stats Level Variation	$X(t)=X_{initial}-10 \cdot t/10= X_{initial}-t$	*Inventory Level Variation*	$X(t)=X_{initial}-15t/5= X_{initial}-3t$
Stats Energy Variation	$X(t)=X_{initial}-10 \cdot t/10= X_{initial}-t$	*Energy Level Variation*	$X(t)=X_{initial}-10 \cdot t/20= X_{initial}-0.5t$
UF : Utility_Work = 1 / (1 + e^(-(Energy - 60) / 8))		*UF : Utility_Work = 1 / (1 + e^(-(Energy - 70) / 10))*	
UF : Utility_Supply = 1 / (1 + e^((Inventory - 40) / 8))		*UF : Utility_Supply = 1 / (1 + e^((Inventory - 50) / 10))*	
Risk Heatmap 3		Risk Heatmap 4	
Simulated Risk Level - Group 3		Simulated Risk Level - Global	
			
Agent Set 3		*Global Aggregated Risk Map from Combined Simulation Groups*	
Initial Inventory Level	*70-90 range (Random)*		
Initial Energy Level	*80 – 100 range (Random)*	*- Consistency of High-Risk Zones Across Groups*	
Stats Level Variation	$X(t)=X_{initial}-20t/5= X_{initial}-4t$	*- Persistent High-Risk Zones Despite Agent Behavior*	
Stats Energy Variation	$X(t)=X_{initial}-20 \cdot t/10= X_{initial}-2t$	*- Risk hotspots concentrated in specific zones*	
UF : Utility_Work = 1 / (1 + e^(-(Energy – 80) / 12))			
UF : Utility_Supply = 1 / (1 + e^((Inventory - 60) / 12))			

Table 17 - Risk heatmaps for Groups 1-3 represent individual simulation outcomes, while the Global map illustrates the combined risk levels from all groups, emphasizing consistent high-risk zones for targeted safety interventions

Differences among the heatmaps from various simulations highlight how changes in *Agent Behavior* can influence the distribution of risk zones. The Risk Heatmap 1, 2 and 3 (Table 17) illustrate shifts in high-risk points, suggesting that minor variations in agent behavior can significantly alter risk zones. Risk Heatmap 4 presents an aggregated heatmap that combines collision data from all four groups. This combined visualization synthesizes the collision frequency across different agent behaviors, offering a comprehensive view of high-risk zones within the construction site. By overlaying the results, the heatmap effectively highlights persistent hot spots where collision risks remain elevated, regardless of behavioral variation among the agents. This combined approach provides a comprehensive view of risk, allowing for a more accurate assessment of areas where recurring hazard situations are concentrated, even with variable agent behavior.

The data gathered from the simulations serves as a valuable decision support tool for the activity and safety planning teams. By representing critical zones in an intuitive manner, the heatmaps enable the identification of high-risk areas that require targeted preventive measures. For instance, red zones near pedestrian pathways and vehicle circulation areas suggest the need to reallocate operational zones or install physical barriers to protect workers from moving machinery. The visual and quantitative information derived from the simulation enables safety managers to adopt proactive solutions, effectively reducing the collision risk on the site. Using heatmaps as a decision support tool facilitates communication and coordination within the safety team by making risk zone information immediately accessible and understandable. Therefore, the simulations offer an essential contribution to planning and safety management, providing concrete data to base preventive and improvement decisions for future construction site operations.

The simulation system has demonstrated significant potential as a support tool for construction site safety management, accurately identifying risk zones and facilitating a visual representation of critical issues. Although still in an initial development phase, the results obtained confirm its effectiveness in identifying hazardous interactions and suggest possibilities for further refinement, such as optimizing agent behavior models and incorporating complex scenarios. This simulation method opens new perspectives for data-driven, proactive safety management, supporting a preventive approach in activity planning for construction sites.

6.4 Discussion

The proposed system, integrating Building Information Modeling (BIM) with Agent-Based Modeling and Simulation (ABMS), represents a significant advancement in pre-construction safety analysis. The development and testing of the system demonstrated its effectiveness in proactively identifying and mitigating risks before construction activities commence. Using advanced platforms such as Unity, a detailed and interactive virtual environment was created, allowing for the simulation of complex construction site scenarios. This environment provided valuable support for safety managers in understanding potential hazards and optimizing safety strategies during the planning phase.

The predictive capabilities of the system, enabled by ABMS, were effectively demonstrated by anticipating risks related to worker movements, equipment interactions, and site configurations. The use of 4D BIM allowed for detailed visualization of the construction process, providing a more comprehensive analysis of the spatial and temporal aspects of site safety. This integration offered a level of insight that traditional safety management approaches often fail to achieve, showcasing the benefits of using simulations to proactively address potential issues.

Testing confirmed that the system was particularly effective in visualizing risks through tools like 3D heatmaps, making it easier to assess risk distribution and prioritize safety interventions. This ability to visually map hazards allowed for clear identification of areas needing attention, ultimately contributing to a safer and more efficient construction planning process.

The system also demonstrated significant potential in improving construction site logistics. By simulating interactions between different site entities, it was possible to optimize the placement of resources, equipment, and materials, reducing waiting times and minimizing interference between activities. This logistical optimization not only enhanced operational efficiency but also reduced the risk of accidents caused by congestion and poor spatial management.

Furthermore, the system showed promising capabilities in integrating safety management directly into the construction workflow. By using simulation outputs to inform planning decisions, it allowed for adjustments in work sequences, task allocations, and equipment positioning to directly address identified risks. This proactive alignment of safety measures with construction activities ensured that safety considerations were embedded into every stage of project execution, ultimately contributing to a more resilient and adaptive construction process.

Overall, the development and testing of the proposed system highlighted its strengths in providing a proactive, data-driven approach to construction safety. However, it should be noted that the framework, partly due to the simplified test model used, presents certain limitations, as described in the following section. By integrating advanced modeling and simulation technologies, the system offers a comprehensive solution for identifying risks, supporting informed decision-making, and enhancing both worker safety and project efficiency.

7 Conclusion

The proposed system, which integrates Building Information Modeling (BIM) with Agent-Based Modeling and Simulation (ABMS), represents a significant advancement in construction safety management. This research has demonstrated how the combination of these technologies, along with the use of advanced modeling and simulation platforms, can provide a more comprehensive and proactive approach to risk management, particularly during the pre-construction phase. The choice of platforms, particularly Unity, has enabled the creation of a highly interactive and detailed virtual construction environment. By leveraging their computational power and flexibility, the proposed framework for the Advanced BIM and AB Simulation System for risk analysis offers safety managers a more dynamic, data-driven approach to construction site planning, focusing on worker safety and the overall efficiency of site activities and schedules.

Utilizing the predictive capabilities of ABMS and the detailed visualization provided by 4D BIM, the system allows safety managers to anticipate risks related to worker movements, equipment interactions, and the overall site configuration, enabling the implementation of preventive measures before physical construction begins. The novelty of this framework lies in its ability to model complex and dynamic site interactions that traditional methods struggle to capture, thereby enhancing the overall effectiveness of safety management.

Furthermore, the system enhances decision-making processes by offering intuitive visualizations, such as 3D heatmaps, which enable users to assess risk distribution across the site in real time. This ability to map potential hazards and optimize site workflows during the planning phase sets a new standard for how construction sites can be managed, prioritizing both safety and efficiency. The flexibility of the proposed system framework, which allows for integration with various BIM datasets, makes it scalable and applicable to a wide range of construction projects, regardless of scale or complexity, positioning it as a versatile tool for the construction sector.

7.1 Research contribution

This research makes a significant contribution to both the academic field and practical applications by developing a system that combines two powerful digital technologies, BIM and ABMS, into a unified framework focused on enhancing safety management. The work extends the traditional use of BIM from a design and construction management tool to an advanced risk analysis tool, which enables proactive safety measures during the pre-construction phase.

A major contribution of this research is the development of a general framework that clearly identifies the data necessary for the system's implementation and establishes a structured basis for integrating BIM and ABMS. This framework emphasizes the need for standardization and a common language for the data and components involved in simulations, thus facilitating interoperability across diverse tools and platforms. The standardization approach presented is essential for scaling up the use of the system beyond simple test cases, enabling its application across the construction industry.

The predictive capabilities of the system provide an innovative way to foresee and mitigate risks that are traditionally challenging to predict using conventional methods. By simulating interactions between workers, equipment, and the environment in a virtual construction site, the system allows safety managers to anticipate hazardous events before physical work begins, contributing to creating safer construction environments. The visual representation and quantification of risks in a way that is accessible and actionable further enhance decision-making processes for safety managers, optimizing resource allocation, reducing delays, and improving project efficiency.

Another significant contribution is the demonstration of the applicability of advanced modeling platforms like game engines, such as Unity, for the creation of interactive and realistic construction environments. This application of platforms, typically used for game development, showcases their potential to enhance construction risk management, thus contributing to the evolution of simulation techniques in the construction industry.

The proposed framework also offers an innovative approach to integrating safety considerations into the design phase. By incorporating safety measures and risk assessments early in the planning process, the research supports a "Safety by Design" philosophy, which is carried throughout the lifecycle of the project. This proactive approach represents a shift from reactive measures to a more forward-looking safety strategy.

Moreover, the research highlights the system's potential as a training tool. The ability to create realistic risk scenarios through simulation provides an opportunity to train workers on recognizing and responding to risks effectively, contributing to a stronger culture of safety. This form of immersive training helps prepare workers for the variable conditions of construction sites and enhances their capacity to make safe and informed decisions in real-life situations.

Finally, the research contributes to the digital transformation of the construction industry by showcasing how digital tools, such as BIM and ABMS, can be integrated to solve real-world challenges and improve safety and productivity. This lays the foundation for developing digital safety standards, potentially leading to the widespread adoption of data-driven and simulation-based safety management practices throughout the construction sector.

7.2 Limitation and opportunities

While the proposed system has demonstrated significant potential, several limitations must be acknowledged to provide a balanced assessment. One of the main limitations lies in the complexity of integrating diverse data sources into a coherent framework. Although standardization efforts were discussed in the research, the practical implementation of such standards remains a challenge. The heterogeneity of data formats and the lack of universally accepted protocols can hinder seamless interoperability, which is essential for effective integration across different construction projects and software environments.

Another limitation concerns the computational requirements associated with running advanced simulations, particularly when scaling up to more complex construction sites with a larger number of agents. The use of game engines like Unity and advanced platforms like NVIDIA Omniverse enables high-quality visualization and interaction, but these tools require substantial computational resources, which may not be readily available for all construction companies, especially smaller firms. The high computational load also presents challenges in achieving real-time responsiveness, limiting the system's applicability for on-site, dynamic decision-making.

The modeling and simulation of human behavior, particularly that of construction workers, also presents notable challenges. The complexity of human decision-making, influenced by experience, situational awareness, and environmental factors, is difficult to replicate accurately in a virtual environment. The developed BIM agent-based models are primarily focused on basic movement and collision avoidance, which does not fully capture the nuances of worker interactions and adaptive behaviors on-site. This limitation restricts the realism and reliability of the simulations, especially when attempting to model more intricate scenarios involving teamwork, multitasking, and decision-making under stress. More sophisticated models could simulate realistic behaviors more accurately, including complex cognitive, social, and emotional factors that influence real-world decisions. Advanced techniques, such as learning agents and multi-agent systems, can provide nuanced behavior simulations by adapting actions based on past experiences or interactions with other agents. This could enhance the realism of the simulation, making it more representative of actual on-site interactions. However, implementing these advanced behaviors requires additional computational resources and expertise, and thus was not feasible within the scope of this study.

Another critical aspect is the validation of agent behavior reliability, a step not addressed in the current framework. Reliable simulation results depend on how closely agent actions mirror those of actual construction workers. While the current system relies on pre-defined, rule-based behaviors, future implementations could verify agent actions against real-world behaviors recorded in construction environments. Observing and analyzing worker behavior on active sites could provide valuable insights into refining agent models, ensuring that they react to situational factors in ways that are consistent with real-world responses. Such validation would enhance the accuracy and reliability of the simulation outcomes.

Moreover, a more thorough data analysis of simulated interactions could reveal additional site dynamics and emergent behaviors not immediately evident in the current setup. Analyzing data more deeply could identify unforeseen events or complex behaviors arising from site interactions, such as bottlenecks, response to hazards, or stress-related decision-making. These insights could lead to the discovery of new risk patterns and help refine site safety measures further. Incorporating advanced data analytics methods, such as machine learning, could enable automated detection of these complex behaviors, providing real-time feedback to site planners.

Additionally, while the framework supports proactive risk assessment during the pre-construction phase, it does not yet fully account for dynamic changes that occur during the actual construction phase. Real-time adjustments to risk assessments are crucial in responding to evolving site conditions, such as unexpected environmental factors or changes in project scheduling. The inability to dynamically update the simulation with real-time data limits the system's effectiveness for continuous risk management throughout the construction lifecycle.

Despite these limitations, there are numerous opportunities for future enhancement and expansion of the system. One key opportunity lies in leveraging emerging technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) to enable real-time data integration and more sophisticated predictive analytics. IoT devices could provide live updates from construction sites, feeding data into the simulation to allow for ongoing adjustments to risk assessments and safety planning. AI techniques could further enhance the accuracy of agent behaviors, making simulations more reflective of real-world scenarios and enabling better decision-making.

Another opportunity involves expanding the agent library to include a wider range of roles, equipment, and environmental conditions, which would enhance the applicability of the system to different types of construction projects. By including a broader spectrum of site entities, the system could model more diverse activities, thereby improving the depth and reliability of risk assessments.

Furthermore, the system has significant potential as a tool for collaborative planning among different stakeholders involved in construction projects. By providing a shared virtual environment where risks are visualized and assessed, the system can foster better communication and understanding between designers, project managers, safety officers, and workers. This collaborative aspect can lead to more informed decision-making and the implementation of more effective safety measures.

Another important opportunity offered by the system is the potential improvement in construction site logistics management. By simulating interactions among different site entities, it is possible to optimize the placement of resources, equipment, and materials, reducing waiting times and minimizing interference between activities. This capability for logistical optimization not only helps improve operational efficiency but also reduces the risk of accidents caused by congestion and poor space management.

In addition, the system has potential applications in worker training. By creating simulations that represent common risk scenarios on construction sites, the system can be used to train workers on how to effectively recognize and respond to risks, contributing to a stronger safety culture. This form of immersive training helps prepare workers for the variable conditions of construction sites and enhances their capacity to make safe and informed decisions in real-life situations.

Finally, the potential use of the system for worker training represents an important area for future development. By enhancing the realism of the scenarios and incorporating more complex agent behaviors, the system could serve as an immersive training platform that prepares workers for the challenges of a construction site, emphasizing safety and situational awareness in a controlled, risk-free environment.

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