DYNAMIC BUILDING MODEL FOR INTERACTIVE HAZARD AND CROWD EVACUATION SIMULATIONS

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SUMMARY*: As safety sciences become more prominent, BIM-based simulations are attracting greater interest from various domains, from fire engineering to crowd management. The integration of BIM with advanced simulation tools and technologies has significantly advanced the field of hazard and crowd evacuation simulations. By providing detailed, dynamic, and interactive models, BIM enhances the accuracy and effectiveness of emergency planning and response strategies. This paper targets the development of a dynamic building model that can facilitate BIM-based fire protection and evacuation planning and training. In current practice, the building model is input to simulation tools as a static model. The latter provides comprehensive information about the building, but this information is static and represents the building in an idealized state where no changes are happening over time. We propose an ontological multi-model framework by extending the information container for linked document delivery (ICDD) implementation, ISO 21597, to a dynamic multi-model container aiming to explicitly allocate multiple dynamic values to elements in the building model. This enables consideration of changeable building spaces during the simulation runtime and hence real-time interoperability of the interlinked simulation components and modules.*

KEYWORDS*: Dynamic BIM, Multi-model, ICDD, real-time hazard and crowd simulation.*

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1. INTRODUCTION

Digitalization has become increasingly prevalent in the Architecture, Engineering & Construction (AEC) industry. Building Information Modeling (BIM) has revolutionized AEC by providing a comprehensive digital representation of a facility's physical and functional characteristics. However, BIM-based safety design and hazard-risk assessment still lag behind disciplines such as structural engineering and mechanical system design (Davidson and Gales, 2021). As safety science gains prominence, BIM-based simulations are attracting increased interest across various domains, including fire engineering and crowd management. The integration of BIM with advanced simulation tools and technologies has significantly advanced the field of hazard and crowd evacuation simulations. By providing detailed, dynamic, and interactive models, BIM enhances the accuracy and effectiveness of emergency planning and response strategies [Wehbe & Shahrour, 2021; Yakhou et al., 2023; Zaman et al., 2024].

The Architecture, Engineering, Construction, and Operation (AECO) market has a high need for simulating complex hazards to enable safe building and evacuation plans. However, current approaches face challenges such as long computing times, a lack of hybrid software, and the requirement for significant expert effort. This often leads to the use of simplified co-simulations for crowd and fire in fixed rooms or sophisticated, separate simulations that are later merged. To achieve precise and reliable simulation outcomes, it is essential to consider the dynamic interaction between fire, occupants, and the building. Eftekharirad et al. (2019) emphasize that providing dynamic information about buildings, occupants, and fire propagation is a key issue and that incorporating dynamic features allows for the real-time transfer of changes in building elements during fire simulation. Building Information Model (BIM) schema IFC (ISO 16739-1, 2018) provides detailed digital data of a built facility designed in a BIM-based software environment. It provides comprehensive geometric and semantic information about the building in addition to the information about the equipment and technical systems inside the building, like furniture and HVAC systems. While the latest IFC model schema offers useful general information as required by fire simulation tools, it still needs to be extended to describe the concrete simulation requirements (Dimyadi 2018).

Building Information Modeling (BIM) has been widely adopted for fire safety planning and evacuation management. However, a significant limitation is that current BIM-based fire evacuation models are primarily static, meaning they do not account for real-time changes in fire dynamics, building conditions, and occupant behavior (Yakhou et al., 2023). These models rely on predefined fire and evacuation scenarios, which limit their ability to respond to evolving emergencies (Sidiropoulos et al., 2020). This static representation fails to capture the dynamic changes that occur within a building during emergencies, such as alterations in spatial configurations due to fire spread or the movement of occupants [Liu & Zou, 2024]. These dynamic changes significantly impact the accuracy and reliability of simulations, limiting their effectiveness for real-time applications and decision-making (Scherer et al., 2018). For instance, fire can spread, smoke can accumulate, and building components can collapse while occupants move and interact with the environment. These dynamic changes affect evacuation routes, visibility, and the overall safety of occupants. Furthermore, the efficient exchange of simulation data with the BIM model to reflect these changes remains a challenge. While dynamic people properties, such as behavior and real-time decision-making, are crucial for realistic real-time simulations [Rasmussen et al., 2019; Rasmussen et al., 2018], this paper focuses on the dynamic aspects of the building model itself. By enhancing the fidelity of the building model, we can better predict how occupants interact with their surroundings and adjust their behaviors in response to changes. Ultimately, this approach aims to foster more effective design strategies that prioritize occupant well-being and optimize energy efficiency in dynamic spaces. The dynamic building model developed in this research provides the necessary foundation for future work that integrates dynamic people properties.

To address these limitations, this paper targets the development of a dynamic building model that can facilitate BIM-based fire protection and evacuation planning and training. The primary research question is: How can a BIM be transformed into a dynamic model that integrates real-time simulation data to support interactive hazard and crowd evacuation simulations? By employing this framework, stakeholders can visualize potential evacuation scenarios more effectively, allowing for better preparedness and response strategies during emergencies. Ultimately, this research aims to bridge the gap between theoretical models and practical applications in fire safety management. The framework tested in the EU project BEST (BEST, 2023), which is a novel real-time hazard and evacuation simulation system for both training and safety assessment purposes. The project required dynamic space changes and interactive rescuer consideration to achieve real-time simulation, and hence, to provide reliable safe building design and safe evacuation plans.

2. STATE OF ART

2.1 Dynamic BIM-based fire safety management

BIM has emerged as a valuable tool for enhancing fire safety management throughout the lifecycle of a building. Research has explored BIM applications across various aspects of fire safety, from design and analysis to emergency response. Early applications of BIM in fire safety focused on design review and code compliance checking. BIM facilitates the automated checking of fire safety regulations, ensuring that building designs adhere to necessary standards [Zhang et al., 2013]. By representing building components and their properties in a digital model, BIM enables efficient identification of potential fire safety deficiencies during the design phase. A significant area of research involves the integration of BIM with fire simulation tools. Fire Dynamics Simulator (FDS) is a widely used computational fluid dynamics (CFD) model for simulating fire behavior. Integrating BIM with FDS allows for more accurate and detailed analysis of fire spread and smoke propagation [Sun et al., 2023]. For example, Sun et al. (2023) developed a BIM-FDS integrated framework for simulating passive fire protection in cross-laminated timber compartments, demonstrating the potential of BIM to support performance-based fire design.

BIM also plays a crucial role in enhancing fire evacuation analysis and planning. Yakhou et al. (2023) presented a framework for integrating fire evacuation models into BIM, facilitating improved collaboration and data exchange between different stakeholders involved in fire safety design. Wehbe and Shahrour (2021) proposed a BIM-based smart system for fire evacuation, utilizing BIM for early fire detection, environmental data evaluation, and optimal evacuation path identification. Liu and Zou (2024) used BIM to support dynamic evacuation path planning in subway stations, adjusting evacuation routes based on real-time fire conditions. These studies highlight BIM's capacity to improve evacuation strategies and enhance occupant safety. Furthermore, BIM has been integrated with other technologies to enhance fire safety. Tang et al. (2019) reviewed the integration of BIM with Internet of Things (IoT) devices for smart building applications, including fire safety. IoT sensors can provide real-time data on environmental conditions, such as smoke and temperature, which can be visualized and analyzed within a BIM environment to improve fire detection and response. Cheung et al. (2018) integrated BIM and Wireless Sensor Networks (WSN) for real-time construction safety monitoring of hazardous gases.

These studies illustrate the diverse applications of BIM in fire safety management. While significant progress has been made, a common limitation in current research is the reliance on static building information (Scherer et al. 2018). This research aims to address this gap by developing a dynamic building model that can capture the changes that occur during a fire event, thus enabling more realistic and effective fire safety simulations.

2.2 Factors affect realistic BIM-based evacuation scenarios

BIM has significantly improved the simulation of hazard and crowd evacuations by providing detailed representations of buildings. Realistic simulations, however, require consideration of several critical aspects. The performance of fire emergency management could be strongly influenced by occupants' different behavior decisions. In their research on fire safety planning, Sun and Turkan (2019) emphasize the need to understand the behavior of evacuees in relation to building and fire parameters. Ma and Wu (2020) developed a BIM-based fire emergency management system that considers the behavior decisions of building users. Based on these decisions, the system plans optimal action routes and sends the occupants visual route guidance via SMS. Within this system, all information on occupant and fire/smoke conditions can be retrieved from the building to update the emergency status continuously. An app on occupants' smartphones is updated with fire locations, fire safety equipment, the safest egress path, and/or location status. In the same contexts, occupants' behaviors in different scenarios can be crucial for evacuation effectiveness and safety. For firefighting and rescue training purposes, Chen et al. (2021) developed a novel framework by integrating BIM, IoT, and virtual reality/augmented reality technologies to improve building fire safety and rescue efficiency. The research outcomes have shown that using fire monitoring and pathfinding indication as external information in an immersive simulated fire environment can reduce the psychological pressure of trainees, reduce the travel distance, and improve firefighting efficiency.

Realistic simulations require the integration of dynamic data, such as changes in the building environment and real-time updates during emergencies. Zheng et al. (2022) proved that planning effective evacuation routes and understanding the usage rates of various evacuation exits are essential for ensuring a safe evacuation process. They create more adaptable and responsive evacuation models using tools like Revit, Pyrosim, and Pathfinder. Moreover, the building's physical characteristics; its geometry, layout, and materials affect how fires spread and how people escape. Beyaz et al. (2021) demonstrated that by linking BIM with agent-based modeling (ABM), more realistic and dynamic simulation results can be achieved to better guide and support disaster management processes. A very realistic and detailed digital environment was created when analyzing evacuation scenarios in the event of a fire accident. In this context, escape routes were created and analyzed, and visibility and accessibility algorithms were performed for the evacuation of people with different profiles. By integrating BIM and ABM, it is possible to model the relationships of people to each other and to the environment within the building, resulting in a more accurate emergency evacuation simulation.

2.3 BIM-based simulations: Challenges and Limitations

BIM-based simulations have taken on an increasingly important role in the construction industry, as they enable efficient planning and implementation of construction projects. However, there are also challenges and limitations associated with this advanced technology that need to be considered. Integrating fire safety considerations into BIM models requires a deep understanding of both disciplines, which can be challenging for researchers and practitioners. Sun et al. (2023) highlighted several obstacles to simulating and designing for construction fire emergencies. Among these complexities are data interoperability and the technical limitations of the currently available BIM software. Seamless data exchange between different software tools and platforms is crucial for effective BIM implementation in fire safety planning, and issues with data transfer processes can hinder progress in this area. Challenges in data exchange between BIM software and fire dynamics modeling tools can affect the accuracy and efficiency of fire safety simulations. Recent research has focused on integrating BIM with other advanced technologies to enhance evacuation simulations. Elsayed et al. (2023) proposed a framework that combines BIM, agent-based simulation, and Bluetooth Low Energy (BLE) technology to optimize evacuation routes and improve real-time tracking of occupants during emergencies. This integration allows for more precise modeling of evacuation dynamics and better management of emergency responses. The complexity of simulating fire behavior in buildings poses challenges for accurately representing fire dynamics in BIM-based simulations, affecting the realism of the results. The realism of such simulations can be impaired as BIM has certain limitations in terms of immersive visualization and interactivity. However, game engines can help to increase immersion and improve the understanding of real-life situations (Zaman et al., 2024). This integration of BIM and game engines makes it possible to refine the visual experience of potential accidents, hazardous areas, and interactive hazards or accident prevention procedures.

3. METHODOLOGY

3.1 Overview of the Methodological Workflow:

In hazardous events, both fire propagation and occupants' evacuation are affected significantly by the building's geometry and space distribution. Hence, both metrics have to be considered in safety design engineering (Onyenobi et al., 2006). Our approach, performed in the frame of the EU project BEST, focuses on extending the recently standardized ICDD framework (ISO 21597), which enables the handling of multiple data resources as a single information container and specifies relationships between the inter-model data using links between the elements in these separate model resources. In the standard, the contents of these links are specified in a Linkset ontology where only static linking is supported, whereas multiple value "dynamic linking" is not available. The proposed methodology here is to extend the Linkset ontology by adopting a "linked list" approach to allow allocating multiple values for a particular element, thereby enabling the use of various building element statuses at simulation run-time in a dynamic manner. The methodological workflow could be outlined as shown in Figure (1). It begins with defining simulation requirements, which include dynamic space changes and interactive rescuer consideration

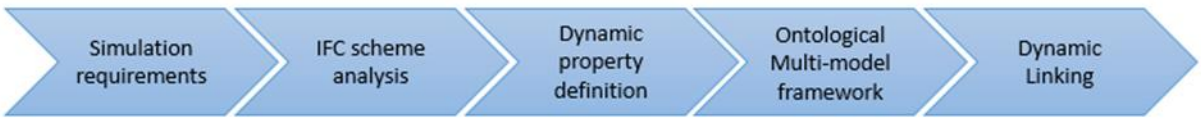

Figure 1: The methodological workflow.

to enable real-time simulation. Next, the IFC schema is analyzed to identify building elements that require dynamic values. These elements are then enriched with dynamic property sets, defining their possible states. The ontological multi-model framework, based on the ICDD standard, is extended using a linked list approach to manage multiple dynamic values for building elements during simulations. Finally, dynamic links are established between building elements and their properties, enabling real-time updates and interoperability between simulation components, such as fire propagation and crowd evacuation, while allowing operator interaction for scenario adjustments.

3.2 Defining simulation requirements:

The simulation requirements for a dynamic fire evacuation system must ensure real-time adaptability, accurate hazard modeling, and seamless interoperability between simulation components. Traditional building information modeling (BIM)-based fire evacuation simulations often rely on static representations of buildings, occupants, and hazards, which limits their ability to reflect real-time changes in emergency situations. To overcome these limitations, the proposed framework must integrate dynamic space modifications, interactive rescuer actions, and evolving hazard conditions within a multimodel ontology-based system. A key requirement is the ability to dynamically update building conditions during the simulation. Elements such as doors, windows, ventilation systems, and fire safety equipment should be represented with multiple operational states (e.g., open/closed, activated/deactivated) to reflect their role in real-time hazard scenarios. The IFC schema (ISO 16739-1, 2018) provides a structured data model for representing building geometry and infrastructure, but it lacks fire-specific dynamic attributes needed for emergency simulations. Therefore, it is necessary to extend the IFC model with additional fire-specific property sets and ensure lightweight, real-time data exchange between BIM and external fire simulation engines. Furthermore, to enable interactive decision-making and emergency response planning, the framework must support real-time interoperability between fire propagation models, crowd behavior analysis, and building state changes. This requires a linked-data approach where multiple simulation components communicate dynamically within an ontology-based multimodel framework. By leveraging real-time data inputs from operator interactions, the system ensures accurate evacuation path adjustments and dynamic hazard response. Additionally, integration with Computational Fluid Dynamics (CFD) and Fast Fluid Dynamics (FFD) models enables the real-time tracking of fire spread, toxic gas dispersion, and environmental hazards, ensuring that evacuation strategies remain responsive to changing conditions. By defining these requirements, the proposed framework aims to bridge the gap between static BIM representations and real-time emergency response systems, ensuring improved safety planning, hazard prediction, and evacuation effectiveness through dynamic, interoperable simulation methodologies.

3.3 IFC schema analysis:

The Industry Foundation Classes (IFC) schema (ISO 16739-1) serves as a standardized data model that facilitates interoperability in the Architecture, Engineering, and Construction (AEC) industry. While IFC models provide comprehensive geometric and semantic data, they primarily represent static building states, limiting their applicability for dynamic fire safety evacuation simulations. Though, the IFC standard is designed to be extensible, allowing for the enhancement of building elements with specific properties needed for specialized domains like fire and crowd simulations (ISO 16739 2013). A critical gap in current IFC-based fire simulations is the lack of support for real-time updates to building elements. During a fire event, occupants may interact with the environment by opening doors, breaking windows, or activating HVAC systems, directly affecting evacuation strategies and fire propagation. However, conventional IFC models lack semantic enrichment mechanisms to reflect these state transitions.

To enable real-time scenario adjustments, the IFC schema is critically analyzed to explore the building elements that are likely to change during an emergency and require dynamic values (Al-Sadoon and Scherer 2021). Building elements such as doors and windows should be assigned state-dependent attributes such as open, closed, or locked, allowing them to function either as accessible pathways or barriers in the simulation. Additionally, material properties, such as fire resistance, influence both fire propagation and occupant movement, necessitating real-time adaptability. Beyond structural elements, dynamic features of building equipment must also be considered. Devices such as alarm systems and HVAC components play a crucial role in fire safety. Electrically powered systems should include status indicators (on/off) and variable operational parameters. For instance, air terminal boxes, which regulate ventilation, should support multiple dynamic attributes, including airflow direction (intake/outrun), activation state (on/off), and power level (ventilation speed). In large spaces, these elements are often networked, requiring a coordinated simulation approach to reflect their impact on air circulation and smoke dispersion. Consider a fire scenario where doors and windows dynamically change states based on occupant actions or automated safety mechanisms. Ventilation systems may deactivate, and alarm devices may activate, altering the evacuation environment. A closed door may act as a barrier, while an open door could serve as an exit, intermediate waypoint, or free passage, depending on the simulation context. These real-time updates must be synchronized within the IFC model and seamlessly mapped to fire and evacuation simulations.

Based on the above, the key building elements that significantly impact fire and crowd evacuation simulations include doors, windows, walls, spaces, and essential safety systems such as Security and Heating, Ventilation, and Air Conditioning (HVAC) devices. These components play a critical role in determining evacuation efficiency, fire spread, and occupant movement. Within the IFC schema, these elements are structured hierarchically, where all physical building components inherit from the *IfcProduct* entity class. The primary IFC entity classes relevant to fire and crowd simulations include, but are not limited to, *IfcSpace, IfcWall, IfcDoor, IfcWindow, IfcFurnishingElement, IfcDistributionElement, IfcSensor,* and *IfcAlarm*. These classifications supports that building elements are accurately represented within the simulation framework, allowing for dynamic interactions and real-time status updates during emergency scenarios.

Table 1: Property set definition and associated IFC class.

IFC class	Property set name	Property Name/Type	Property Definition
IfcDoor	Pset_Door Status	Door Status/ IfcList	Define whether the door status is *open*, *closed* or *locked*.
IfcDoor	Pset_Door Type	Fire Door/ IfcBoolean	Define the door type whether it is a fire door or not. *true* for the fire door, *false* for not.
IfcWall	Pset_Wall Type	Breakable Wall/ IfcBoolean	Indication whether the wall is breakable or not (when exploded in a hazardous event or broke for rescue purposes). *true* for breakable wall, *false* for not.
IfcWindow	Pset_Window Status	Window Open/ IfcBoolean	Indication whether the initial window status has changed from open to close (or vice versa) due to interaction between Occupants, Fire and building. *true* for open, *false* for not.
IfcDistribution Element	Pset_HVAC Status	HVAC_Activated/ IfcBoolean	State the HVAC status before and after fire. o*n* for activated HVAC, o*ff* for not.
IfcFireSuppression Terminal	Pset_Sprinkler Status	Sprinkler_Activated/ IfcBoolean	State the Sprinkler status before and after fire. o*n* for activated Sprinkler, *off* for not.

3.4 Dynamic property definition:

The IFC schema provides a generic framework for representing building components, allowing for flexible extensions through the use of property set definitions (PSD) rather than modifying core entity structures. Property sets define additional attributes for building elements, utilizing various data types, including single values, enumerations, bounded values, tables, references, lists, and property occurrences. These custom property sets ensure that dynamic features such as state transitions (e.g., open/closed, activated/deactivated) for fire and evacuation simulations can be efficiently represented. To maintain consistency with IFC standards, these property sets adhere to the IFC property set definition (PSD) sub-schema. In this study, five critical IFC entities were extended with dynamic properties: IfcDoor, IfcWall, IfcWindow, IfcDistributionElement, and IfcFireSuppressionTerminal. Each entity was enriched with additional attributes to support real-time scenario adjustments, ensuring that fire propagation, evacuation planning, and building state updates can be dynamically simulated. The specific property sets and their associated parameters are detailed in Table 1, outlining how these enhancements facilitate real-time interactive simulations.

To generate the property set file, a prototype software tool named "IFC Property Set Extender" was developed, as will be explained in section 4.1. This software is designed to define extended property sets for various building elements using a predefined property set template. Additionally, it enables the assignment of multiple values to extended properties, facilitating that dynamic attributes can be incorporated into IFC-based fire and evacuation simulations. For example, to extend the semantic information for the doors, the property set name and definition are defined, and the applicable entity is selected; here it is the IfcDoor, and then the property values are presented for the door: “Open,” “Closed,” and “Locked.”Listing 1 below shows a snippet of the Property_set model for an IfcDoor.


```
{  "name": "Pset_DOORSTATUS",
   "definition": "Properties common to the definition of all occurrences of IfcDoor.",
   "hasProperties": [
      {
         "type": "IfcPropertySingleValue",
         "valueType": "IfcText",
         "definition": "Indication whether the element is open or close or locked.",
         "propertyName": "DOOROPEN",
         "guid": "25e5f73d-238a-4fa0-8b6f-0295d185ca17",
         "listvalue": [
            "Close",
            "Open",
            "Locked"
         ] }  ] }
```


Listing 1: Property set model for IfcDoor.

3.5 Ontological multi-model framework:

3.5.1 The ICDD structure

The Information container for linked document delivery is the result of a synergy of efforts that spanned over a decade. These efforts started in Germany with the emergence of the multimodel approach, firstly developed in the Mefisto project (Scherer and Schapke, 2011; Fuchs et al., 2011), and the Netherlands in the COINS project that developed an interdisciplinary container for the exchange of information (Hoeber et al., 2015).

The ICDD, designated as ISO 21597, is an international standard that specifies ontological-based containers to facilitate the exchange, storage, and archiving of heterogeneous documents. Various types of files can be included within a single container, such as textual documents, images, models, and other digital resources. Moreover, it enables the linking of documents within the container as well as the creation of relationships between different data elements within those documents. The standard incorporates guidelines for securing the exchange of information containers and ensuring their archiving, data integrity, and accessibility. As a result, ISO 21597 is designed to streamline the management of information related to complex projects, especially in the fields of construction and engineering (ISO 21597).

The hierarchical structure of the ICDD comprises an index file and three folders: (1) the Ontology Resources folder, where the ontology files Container.rdf and Linkset.rdf are located; (2) the Payload Documents folder storing the internal linked models; and (3) the Payload Triples folder, where all the link datasets are stored (Figure 2 on the left). The index file contains all the meta-data to describe the container and to specify the documents that make up its contents.

3.5.2 Linked list approach

A linked list is a linear data structure that stores a collection of data elements dynamically. It forms a series of nodes connected by pointers, where each node stores the data and the address of the next node (Parlante, 2001). In our approach, the concept of the doubly linked list is selected to facilitate the allocation and search of multiple values for a building element in the IFC model. The linked list data structure is used to manage multiple dynamic values for building elements during simulations. Each node in the linked list represents a specific state of a building element (e.g., door open, door closed), allowing for real-time updates and interoperability between simulation components. This approach enables the framework to track changes in building elements (e.g., doors, windows, HVAC systems) and propagate these changes to the fire and crowd simulation modules in real-time. It proved its efficiency to extend the Linkset ontology.

3.5.3 The Proposed extended ICDD ontology

As mentioned, to achieve the envisaged dynamicity for building elements, the Linked List data structure is used to extend the Linkset ontology, which is defined as an RDF(S)/OWL file providing the object classes and properties used to specify links between documents, models, and their elements in the container. The Linkset ontology specifies different linkage capabilities to link, for example, between a single element in a model and a related document, one element in one document/model and multiple related elements in other documents/models, or among a set of elements in one document/model and related elements in multiple documents/models. Each link element in a linkset is related to exactly one internal/external document where the element has only one static value. To link an element using the optional hasIdentifier property, the element should have an identifier. There are three mechanisms to identify an element in a document: a string-based identifier, a query, or a URL-based identifier.

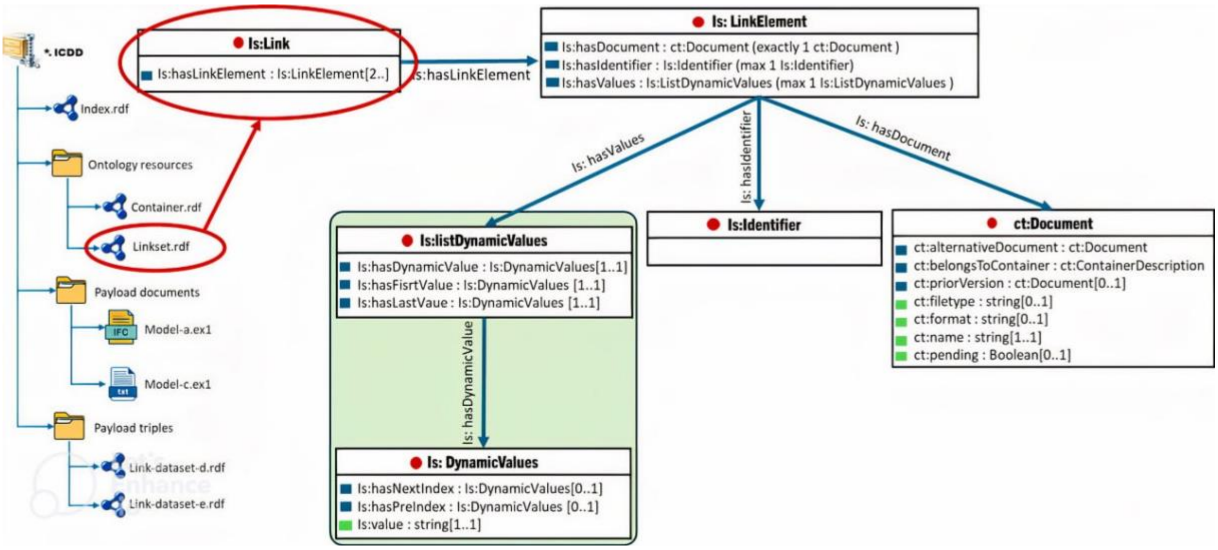

Figure 2: Linkset ontology showing the standard schema and the proposed extension (inside the green box) (based on Al-Sadoon et al., 2022).

A standard ls:link has not less than two ls:LinkElement, each referencing ls:hasDocument and an optional ls:hasIdentifier. The proposed extended schema for the Linkset ontology, highlighted in the green box in Figure 2, is developed to support deep model-based linking; hence, ls:hasIdentifier is not optional here. The ls:LinkElement is extended to include a third object property named ls:hasValues to reference the added new object class ls:listDynamicValues, which in turn consists of the three object properties that have been respectively named ls:hasDynamicValue, ls:hasfirstValue, and ls:haslastValue. ls:hasDynamicValue references the second newly added object class ls:DynamicValues, which also consists of three object properties that have been named ls:hasNextIndex, ls:hasPreIndex, and ls:value. The newly added objects, object properties, and datatypes for the linkset ontology are listed in Table 2.

Unlike the standard IFC model, where a data attribute typically has only one value, the extension for the Linkset ontology provides for an externally maintained multimodel-based linked list approach, which facilitates assigning multiple explicit values for a building element attribute. This allows for different application scenarios of tracking the variation of a value throughout a project's lifecycle within the same building model. Instances for the Extended Linkset ontology shown in Appendix A.

Table 2: Extended Linkset ontology definitions.

Named entity	Description
Object	
ls:listDynamicValues	A class referencing to a list of dynamic values
ls:DynamicValues	A class referencing to dynamic values
Object type	
ls:hasValues	A relation from *ls:LinkElement* to an *ls:listDynamicValues*
ls:hasDynamicValue	A relation from *ls: listDynamicValues* to an *ls:DynamicValues.*
ls:hasfirstValue	Referencing to the first value in a list of dynamic values
ls:haslastValue	Referencing to the last value in a list of dynamic values
ls:hasNextIndex	A relation from *ls:DynamicValues* to a next *ls:DynamicValues*
ls:hasPreIndex	A relation from *ls:DynamicValues* to a previous *ls:DynamicValues*
Datatype	
ls:value	A String containing the value.

3.6 Dynamic linking

Building on the dynamic property definition established in Section 3.4 and the ontological multi-model framework introduced in Section 3.5, the dynamic linking mechanism ensures real-time interaction between building elements, fire simulation models, and crowd evacuation systems. While the IFC schema (ISO 16739-1) provides a structured representation of building elements and their attributes, it does not inherently support real-time updates required for dynamic fire evacuation scenarios. To overcome this limitation, the proposed framework leverages the ICDD (ISO 21597) multimodel approach, enabling semantic relationships between static BIM data and evolving simulation parameters.

The dynamic linking process follows a structured approach where building elements are connected to their corresponding dynamic property sets within the Multimodel Container. Each link defines a semantic relationship between a building element's static representation in the IFC model and its attributes in the property set model. For example, an IfcDoor in the IFC file is initially linked to a DoorStatus property set file, which can transition between "open," "closed," and "locked" states based on real-time fire and evacuation conditions.

The added object property ls:hasValues, illustrated in Figure 2, facilitates the real-time exchange of updated building element states between the Multimodel Container and the simulation tools. When a simulation scenario is initiated, the operator defines the scenario and chooses the first value for the door status to be "open". Based on the linked list data structure, this value becomes the first node in the linked list and the current value. The current building elements' status is transmitted to the simulation engines, allowing them to start with the correct environmental conditions. As the simulation progresses, the operator could pause the simulation and change the door status to become "closed". Again, based on the linked list data structure, this value becomes the second node in the linked list and the current value, instead of the first value, and so on. When the simulation resumed, the last value, which has become the current value, was sent to simulation tools. This ensures that the simulation environment remains synchronized with real-world emergency response scenarios, providing a realistic and adaptive framework for fire evacuation planning.

```
<listDynamicValues rdf:about="#9169a827-b9b5-11ec-98e8-425bd824278f">
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#NamedIndividual"/>
 <firstValue rdf:resource="#9169a826-b9b5-11ec-9b6c-425bd824278f"/>
 <lastValue rdf:resource="#648da6e9-b9b7-11ec-94be-425bd824278f"/>
 <hasDynamicValue rdf:resource="#9169a826-b9b5-11ec-9b6c-425bd824278f"/>
 <hasDynamicValue rdf:resource="#648da6e9-b9b7-11ec-94be-425bd824278f"/>
</listDynamicValues>
```

4. FRAMEWORK VERIFICATION

A prototype of the framework was tested as part of BEST project. A dynamic change in space and an interactive rescuer consideration were required to achieve real-time simulation and consequently, ensure reliable safe building design and safe evacuation plans. BEST comprises several modules: an advanced fire, toxic gas, and CBRN dispersion computational fluid dynamics (CFD) simulation module; an advanced crowd simulation module, a new real-time training module with dynamic rescue scenarios; a multimodel framework with an ontology-based link approach; and a dynamic building information model (BIM) regarding open/closed doors, windows, HVAC, and other relevant changes of the scenario space.

To validate the proposed approach, a two-story university building in Prague was used as a pilot case study. The two-story university building, created as a pilot model for concept verification, comprises lecture rooms, labs, offices, and other building utilities, all of them furnished and equipped with HVAC and sprinkler systems as illustrated in Figure 3.

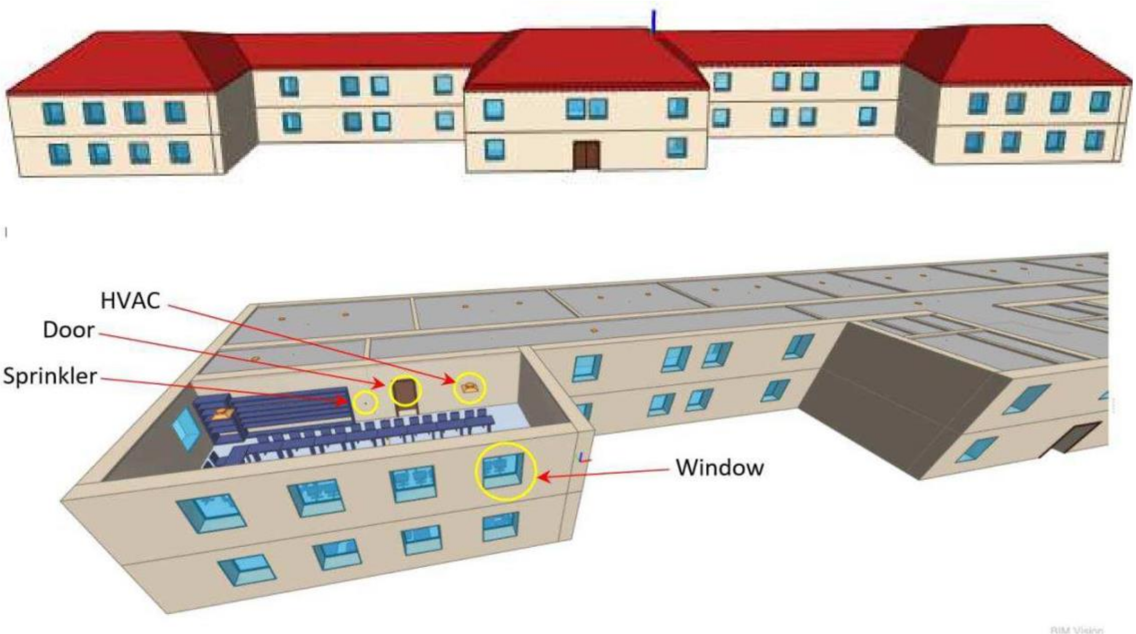

Figure 3: University building model.

The approach is implemented in the form of two independent, interacting services, namely (1) IFC Property Set Extender, used to enhance an IFC model via a separate linked property set model, and (2) Multi-model Engine (MME), supporting the creation and manipulation of ICDD data based on the proposed extended ICDD schema and providing for the integration and use of dynamic BIM features. Integration with other platform components is achieved using REST API with requests and responses formalized in JSON. Functions provided by these services are managed by a service called Scenario Rescue Team Manager (SRTM), which plays as an orchestration services in the platform. It manages the semantic multi-model, provides the numerical simulation modules with their time-dependent models, and provides the end user with a graphical interface for defining and controlling the scenarios to be simulated (see Figure 4).

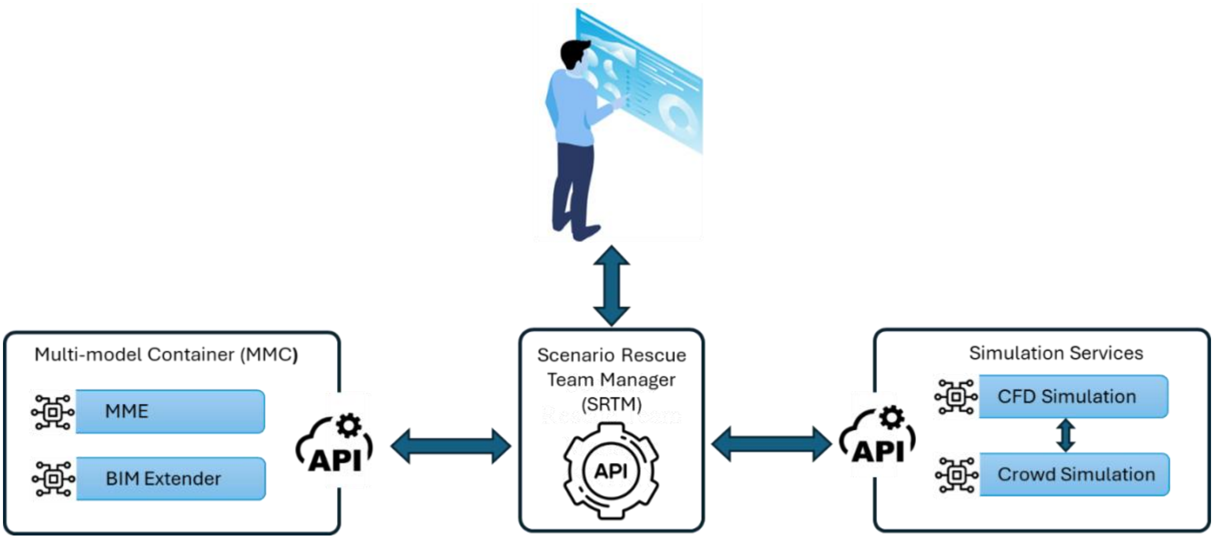

Figure 4: Top-level services of the BEST platform.

During the simulation, the end user can temporarily stop it and edit the scenario. For example, at some point, the end user (a safety designer) can decide to change the door type from a normal door to a fire door or to change the status of lab benches to be removable in order to assess how these property changes would affect the fire and crowd simulation. In another context, the end user (safety training team) can decide to change the property of a window to be a breakable window to be used for rescue and thereby define an additional possible escape path. Then the end user will resume the simulation to assess the effect of the change on the propagation of the fire and the crowd evacuation.

4.1 IFC Property Set Extender

The BIM model contains a high level of semantic information that can enhance the input data for a simulation used for fire propagation and crowd evacuation (Sun and Turkan, 2019). Building models are modeled in third-party CAD applications (e.g., REVIT, ALLPLAN) and exported in standardized formats, preferably in the BIM/IFC schema according to ISO 16739. The properties of the model elements are static in this format and can only be used to a limited extent for dynamic co-simulation. However, the available BIM object libraries are currently not mature enough to supply fire and smoke simulations with enough information (Davidson and Gales, 2021). To respond to the deficiency of property parameters specific to fire events, the IFC Property Set Extender service (Figure 5) was developed to enrich the BIM data with behavior and interaction information and the related possible object status. In alignment with the overall multimodel approach, the extended BIM data are thereby made available without disturbance to the content of the original BIM data. A user interface allows creating an IFC Property set file to extend the semantic information of any building element, which is then exported as a JSON file and added as an internal document to the Multimodel Container.

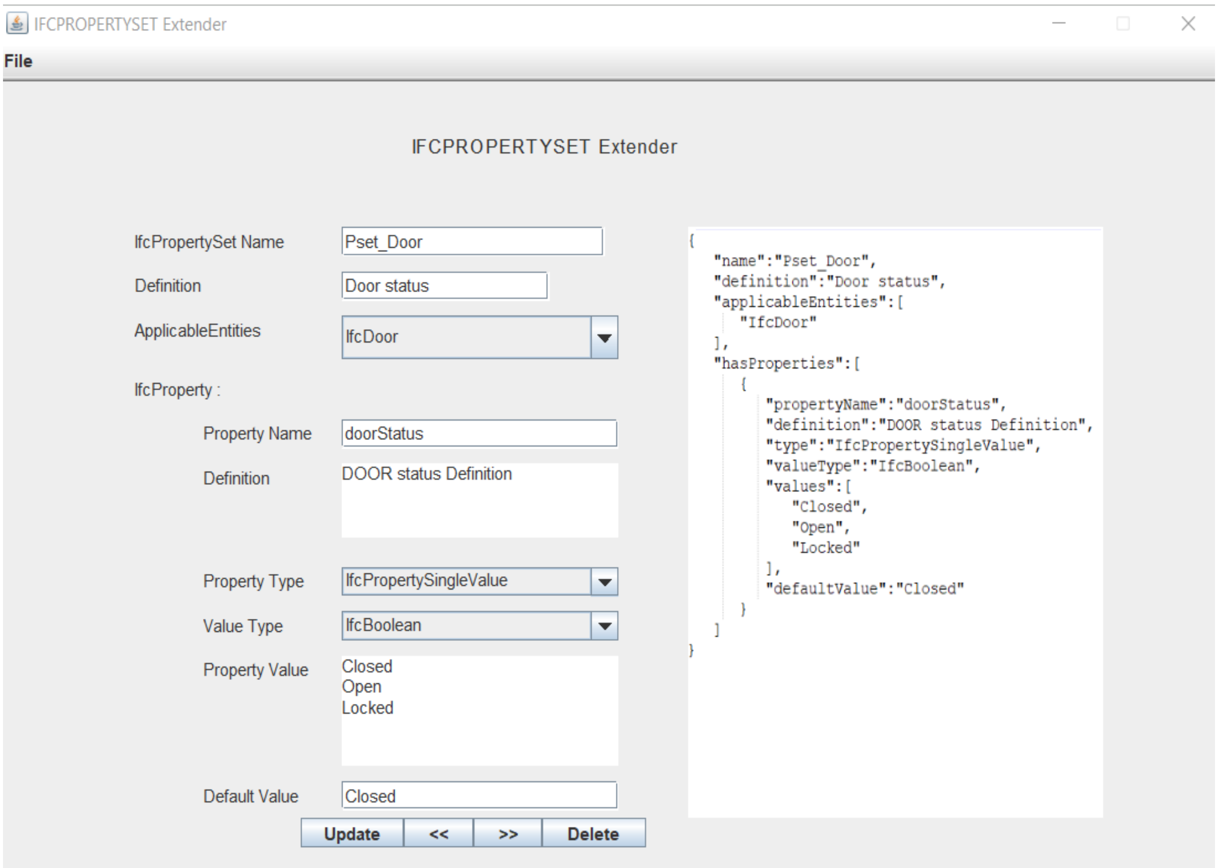

Figure 5: IFC Property Set Extender User Interface (based on Al-Sadoon and Scherer, 2021).

For the university building model in our use case, the dynamic features of the building elements that may be changed as a consequence of the interaction between the occupants and the building elements during fire simulation were explored. Then, building elements that need to be enriched with dynamic properties were defined. Building elements such as doors, windows, walls, spaces, and security devices, as well as heating, ventilation, and air conditioning (HVAC) devices, are considered to be the most relevant objects of a building. Therefore, the property descriptions of the most important model elements required for co-simulation were expanded to enable them to be changed dynamically and to model any time-dependent states (see Table 2).

Dynamic elements are specified in the exchange data structure of a scenario as a list of JSON objects, which are structured as follows:

{ "elementID": "0rPybmzWL19g0khw4YUW$k",

"elementType": "IfcWindow",

"state": "OPEN"}

The *elementID* represents the IFC *GUID* of the element in the BIM model to enable a clear assignment by the simulation tools. The *elementType* specifies the type of element, whereby in principle all element types defined in the IFC standard are permitted. *State* represents the current state of an element. In the case of windows and doors, one of the states *OPEN*, *CLOSED*, or *LOCKED* could be selected. Elements of type *IfcSprinkler* have either ACTIVATED or *DEACTIVATED* state, and so on (see Table 2). This representation method can be extended as desired, and in the case of future, potentially more complex element types, it is also possible to add further attributes. In this way, even complex states can be represented as a vector of several attributes.

The developed concept allows the definition of any property and state values and thus a non-invasive extension of building models for any simulation tasks. The number and type of attributes are not limited in principle in the SRTM but are determined by the capabilities of the simulation software used. In our use case, property sets are bundled in an elementary model together with the building model and added as internal documents in the multi-model container.

4.2 Mutli-model Engine (MME)

ISO 21597 provides specifications for handling multiple documents as one information delivery in a container and specifications to describe means of linking among these documents. The ICDD, as a generic information container format, is used to store and exchange such linked data. In our implementation, the proposed extended version of the ICDD is applied to achieve the desired dynamicity.

The MME role in the co-simulation scenario is to provide the following functions (Figure 6):

1. *Create the Multimodel Container* as specified in the ontologies Container.rdf and Linkset.rfd;

2. *Add elementary models* that can be any kind of data sources to be saved either internally in the container or kept at their sources and referenced by URL. In the discussed use case, the elementary models are the IFC building model in IFC format and property set files in JSON format.

3. *Create links* based on the object classes and properties provided by the Linkset ontology, whereby each link specifies interdependencies among two or more elements contained in the elementary models.

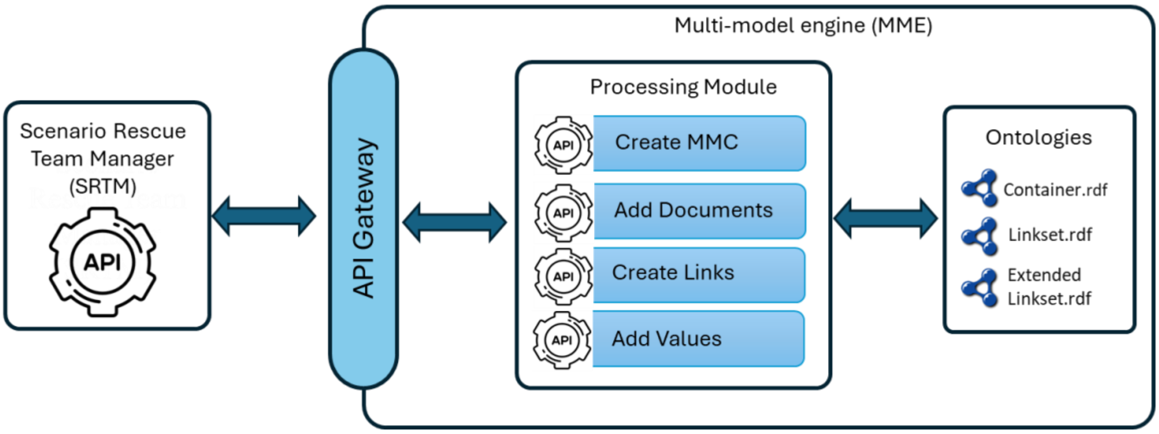

Figure 6: Functions of the Multi-model engine.

The developed extended specification provides multiple linkage capabilities. In the case study, links are created between building objects and their related pre-defined property sets. For example, the *IfcDoor* entities are linked to the property *door status*. Then, based on the extended Linkset ontology, the defined values for this property are added as a linked list and used dynamically during the simulations running time.

4.3 Prototype implementation

The BEST platform aimed to be provided as Software as a Service (SaaS) for training and safety assessment purposes. The platform provides a graphical interface and functions for creating semantic scenario models and defining scenarios, person profiles, disasters, and monitoring and controlling dynamic components of simulated scenarios. The services also enable the end user to start a simulation, pause it, examine and edit the scenario, resume the simulation, and finally make informed decisions on the basis of the obtained results and thus imitate a rescue worker (Figure 7).

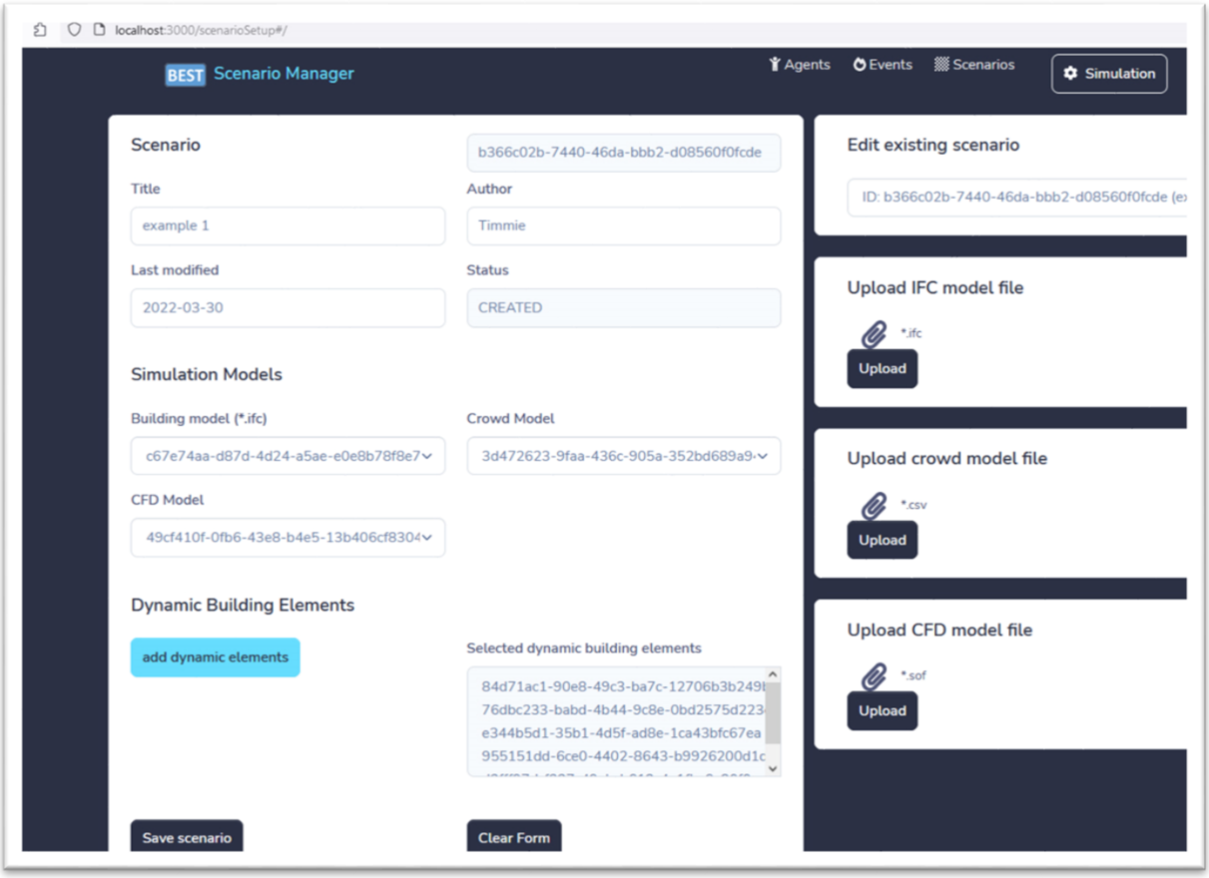

Figure 7: Scenario manager user interface.

To implement the simulations, the operator needs to follow the following steps:

1. Upload the building model. The MME creates a multi-model container and adds the building model.
2. Define additional property set(s) using the IFC Property Set Extender interface, add the created property set files into the multi-model container, and then link them to the relevant elements in the building model.
3. To prepare a scenario, the operator shall use *Edit existing scenario*. It has pre-defined scenarios that could be changed based on scenario requirements. The operator can change or add any parameter in the selected scenario to create the starting scenario.
4. The scenario settings are prepared and transformed into a JSON representation and attached to the message body (Appendix B).
5. In order to start the simulation, it is necessary that Crowd Simulation and Fluid Dynamics engines read and prepare the BIM file; they prepare the layout of the object for simulation, and they initiate the communication between themselves.
6. Before starting the simulation, both Crowd Simulation and Fluid Dynamics engines need to be ready. This could be confirmed by checking the ready message at the Crowd simulation Server console. To start the simulation, click on *Start Simulation* button (Appendix C).
7. In Crowd simulation client window, the counting shown in the upper left corner is the simulation time and fires and smokes (Figure 8).

Figure 8: Crowd simulation client window after start the simulation.

8. To make changes to an ongoing simulated scenario, click on *Pause Simulation* button, and both engines will pause (the counting of simulation time and fires and smokes will stop). Then the operator can make changes to the simulation scenario, e.g., change the door state from close to open to reflect opening a door through the interaction of people and buildings in the fire location and remove agents. To continue simulation, click on *Resume*, the new changes are automatically triggered by the numerical simulation, thereby expanding the simulation space. The simulation is continued with the automatically changed models after a semantic persistence check. The simulation time and fires and smoke at the upper left corner of crowd simulation client window will start counting again as shown in Figure 9.

Figure 9: Crowd simulation client window after resume the simulation.

9. The previous step could be repeated until the operator gets the required scenarios, then click on *Stop Simulation* to end the simulation.

10. To analyse the simulation outcomes, the injuries of agents and their absorbed contaminant values are

exported in an output CSV file. These outputs allow the operator to analyse how user-driven dynamic changes (e.g., opening a breakable window or locking a door) affect hazard spread and crowd evacuation performance.

5. DISCUSSION AND LIMITATIONS

This research introduces a novel dynamic multi-model framework by extending the ISO 21597 ICDD standard to support dynamic hazard and evacuation simulations in buildings. The proposed approach addresses the significant limitation in current BIM-based simulation practices, where building models are treated as static entities during runtime. By enabling multiple dynamic values to be assigned to building elements, the framework supports a more accurate and temporally responsive simulation of building environments under emergency conditions.

5.1 Research Contributions:

One of the central contributions of this study is the semantic extension of the ICDD schema using a doubly linked list structure. This novel approach allows each building element to carry a history of value changes, making it possible to track and dynamically update attributes such as door status, window state, HVAC activation, or sprinkler functionality during a simulation. This contribution not only supports real-time responsiveness but also opens avenues for tracking changes across the entire building lifecycle—from design to facility management. A second major contribution is the development of the BIM Extender and Multi-model Engine (MME) as standalone services that integrate seamlessly with simulation environments via REST APIs. The IFC property set extender enables domain experts to enrich IFC models with domain-specific dynamic attributes in a non-invasive way, preserving the integrity of the original model. The MME provides automated creation and management of multi-model containers, dynamically linking BIM models to simulation properties and enabling runtime edits. Thirdly, the framework was successfully implemented and tested in a real-world scenario within the BEST project, using a detailed two-story university building model. This implementation demonstrated the framework's ability to simulate real-time changes in building behavior and validate emergency strategies based on dynamic environmental and spatial changes. The framework allowed users to interactively modify property states mid-simulation (e.g., designating breakable walls or changing door types) and assess their impact on hazard spread and evacuation behavior.

5.2 Limitations:

Despite the promising outcomes, the framework has limitations. Currently, only a limited set of building elements and dynamic attributes have been modeled and tested. Expanding this set, especially to incorporate a broader variety of sensors and actuators, could pose performance and storage challenges, particularly when large volumes of time-series data are involved. Furthermore, the simulation does not yet incorporate pedestrian psychology, group dynamics, or cognitive decision-making models. The absence of these human-centric factors can limit the realism of crowd behavior during emergencies. Future extensions should address this gap by integrating agent-based behavioral models or linking with crowd behavior simulators that consider emotional states and group interactions. Lastly, the framework assumes technical interoperability across BIM, simulation, and semantic models, which may not always hold in heterogeneous environments. Additional work is required to ensure robust data translation across platforms and to optimize performance when scaling to larger or more complex structures.

In summary, this study provides a foundational step toward making BIM-based simulations dynamic, interoperable, and interactive. By combining a formal extension of the ICDD schema with practical services and use case validation, it contributes both theoretical and applied advancements to the field of digital construction and safety management.

6. CONCLUSION AND FUTURE WORK

The research highlights the importance of considering dynamic features in safety design and evacuation planning, offering valuable insights for future developments in this field. It introduced a dynamic BIM-based framework that enhances real-time fire evacuation simulations by enabling runtime changes to building elements through semantic multi-model linking. By extending the ISO 21597 ICDD standard with a doubly linked list structure, the study overcame a fundamental limitation in conventional BIM-based simulations—their static nature. The proposed approach allows simulation tools to access and apply dynamically changing properties (e.g., door states, HVAC activation, or wall breakability) in response to user interaction or environmental events. The integration of the IFC Property Set Extender and Multi-model Engine (MME) into a co-simulation platform was validated in a case study using a two-story university building. Operators were able to modify building attributes mid-simulation and observe impacts on fire and crowd dynamics, while simulation outputs (e.g., agent injuries and contaminant exposure levels) were captured for evaluation, supporting scenario-based decision-making.

The findings demonstrate that dynamic interaction between the BIM model and simulation tools can improve scenario realism, support safer building design, and enable more responsive emergency training. While this framework presents a major step forward in dynamic simulation integration, limitations remain. These include the current focus on a limited set of building components, and the absence of cognitive and behavioral models for occupants. Additionally, large-scale deployment will require optimization for performance, interoperability, and automation.

Future work will focus on three primary directions. First, the integration of occupant behavior and group dynamics models will allow simulation environments to reflect more realistic crowd responses to evolving hazards. Second, the framework will be extended to support integration with real-time IoT sensor networks and streaming data, enabling digital twins that reflect both environmental and human factors in emergencies. Third, the framework will be generalized to support dynamic model updates across the entire building lifecycle, allowing for change tracking between design, construction, and facility management, including applications such as version control, cost analysis, and as-built verification. These extensions aim to enhance the framework's adaptability, scalability, and contribution to holistic digital construction and safety engineering.

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Authors contribution: Nidhal Al-Sadoon: Conceptualization, Methodology, and writing – original draft and final version. **Raimar J. Scherer**: Supervision. **Karsten Menzel:** Supervision. **FIDES DV-Partner** and **GmbH T-SOFT a.s.:** Simulation development and implementation.

REFERENCES

Al-Sadoon, N., Katranuschkov, P., & Scherer, R. J. (2023). Extending ICDD implementation to a dynamic multimodel framework. In ECPPM 2022—eWork and eBusiness in Architecture, Engineering and Construction 2022 (pp. 115-122). CRC Press.

Al-Sadoon, N., & Scherer, R. J. (2021). IFC semantic extension for dynamic fire safety evacuation simulation. In Proceedings of the CIB W78 Conference (Vol. 2021, pp. 11-15).

BEST Project (2020-2023). Real-time building evacuation simulation & training system for airborne hazards & fire. Retrieved June 15, 2024, from http://www.bestsim.eu/.

Beyaz, C., Özgener, E. D., Bağcı, Y. G., Akın, Ö., & Demirel, H. (2021). Integration of building information modeling and agent-based modeling for evacuation simulation. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 46, 109-112.

Chen, H., Hou, L., Zhang, G. K., & Moon, S. (2021). Development of BIM, IoT and AR/VR technologies for fire safety and upskilling. Automation in Construction, 125, 103631. https://doi.org/10.1016/j.autcon.2021.103631

Davidson, A., & Gales, J. (2021). BIM and fire safety engineering—overview of state of the art. International Journal of High-Rise Buildings, 10(4), 251-263. https://doi.org/10.21022/IJHRB.2021.10.4.251

Dimyadi, J., Solihin, W., & Amor, R. (2018, May). Using IFC to support enclosure fire dynamics simulation. In Workshop of the European Group for Intelligent Computing in Engineering (pp. 339-360). Springer International Publishing.

Eftekharirad, R., Hosny, A., Nik-Bakht, M., & Hammad, A. (2019). Planning building renovation projects for safe evacuation provisions—an agent-based modelling approach. In Proceedings of the 16th IBPSA (pp. 2294-2301). https://doi.org/10.26868/25222708.2019.210897

Elsayed, P., Mostafa, H., & Marzouk, M. (2023). BIM-based framework for building evacuation using Bluetooth Low Energy and crowd simulation. Journal of Building Engineering, 70, 106409.

Fuchs, S., Kadolsky, M., & Scherer, R. J. (2011). Formal description of a generic multi-model. In Proceedings of the 20th IEEE International Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprises (pp. 205-210). IEEE.

Hoeber, J. G., Alsem, D. M., & Willems, P. H. (2015). The management of information over the life-cycle of a construction project using open-standard BIM. In Proceedings of the 32nd CIB W78 Conference, Eindhoven, The Netherlands (pp. 295-301).

International Organization for Standardization. (2018). ISO 16739-1: Industry foundation classes (IFC) for data sharing in the construction and facility management industries—Part 1: Data schema. Geneva, Switzerland.

International Organization for Standardization. (2020). ISO 21597-1: Information container for linked document delivery—exchange specification—Part 1: Container. Geneva, Switzerland.

Li, H., Lu, M., Chan, G., & Skitmore, M. (2015). Proactive training system for safe and efficient precast installation. Automation in Construction, 49(A), 163-174. https://doi.org/10.1016/j.autcon.2014.10.010

Liu, Z., & Zou, R. (2024). Dynamic evacuation path planning for subway station fire based on IACO. Journal of Building Engineering, 86, 108828.

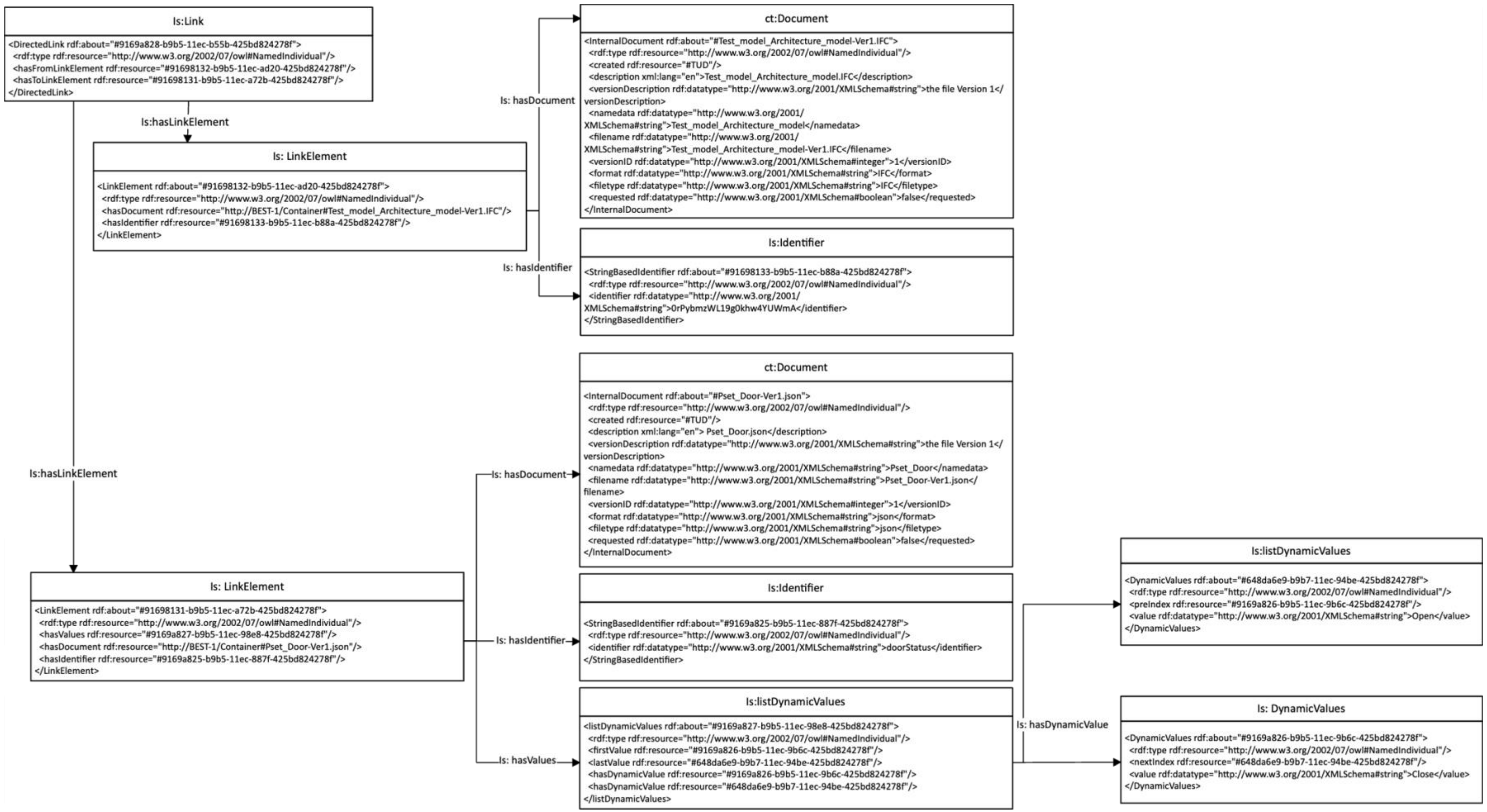
Ma, G., & Wu, Z. (2020). BIM-based building fire emergency management: Combining building users' behavior decisions. Automation in Construction, 109, 102975. https://doi.org/10.1016/j.autcon.2019.102975

Onyenobi, T., Hudson, J., & Ormerod, M. (2006). Impact of building geometry on fire spread rate. In Proceedings of the 22nd Annual ARCOM Conference, Birmingham, UK (pp. 739-744).

Parlante, N. (2001). Linked list basics. Stanford CS Education Library, 1, 25.

Rasmussen, M. H., Lefrançois, M., Pauwels, P., Hviid, C. A., & Karlshøj, J. (2019). Managing interrelated project information in AEC Knowledge Graphs. Automation in Construction, 108, 102937.

Appendix A:



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Appendix B:


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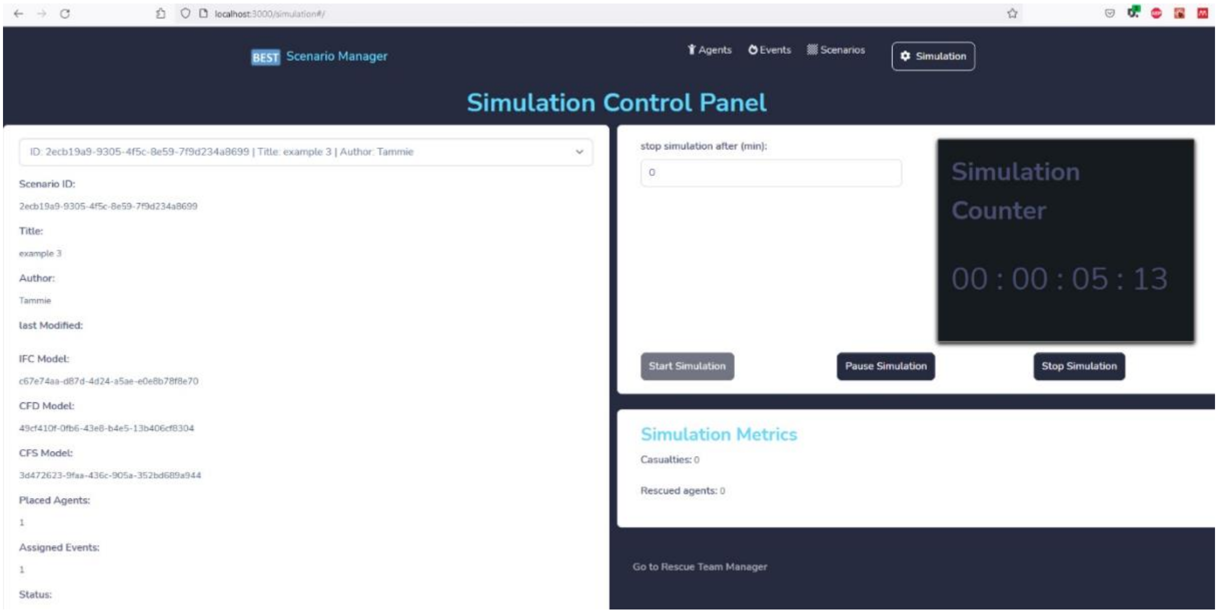
```

Appendix C:



localhost:3000/simulation#/
BEST Scenario Manager
Agents
Events
Scenarios
Simulation
Simulation Control Panel
ID: 2ecb19a9-9305-4f5c-8e59-7f9d234a8699 | Title: example 3 | Author: Tammie
Scenario ID:
2ecb19a9-9305-4f5c-8e59-7f9d234a8699
Title:
example 3
Author:
Tammie
last Modified:
IFC Model:
c67e74aa-d87d-4d24-a5ae-e0e8b78f8e70
CFD Model:
49cf410f-0fb6-43e8-b4e5-13b406cf8304
CFS Model:
3d472623-9faa-436c-905a-352bd689a944
Placed Agents:
1
Assigned Events:
1
Status:
stop simulation after (min):
0
Simulation Counter
00 : 00 : 05 : 13
Start Simulation
Pause Simulation
Stop Simulation
Simulation Metrics
Casualties: 0
Rescued agents: 0
Go to Rescue Team Manager