2024 European Conference on Computing in Construction
Chania, Crete, Greece
July 14-17, 2024

DEVELOPING A BUILDING SIMULATION IDENTITY CARD FOR ENHANCED SAFETY AND COLLABORATION IN EMERGENCY EVACUATION SIMULATION

Muhammad Farhan Jahangir[1], Aliakbar Kamari[1], and Carl Peter Leslie Schultz[2]
[1] Department of Civil and Architectural Engineering, Aarhus University, Aarhus, Denmark
[2] Department of Electrical and Computer Engineering, Aarhus University, Aarhus, Denmark

Abstract

Ensuring that a building can be safely evacuated in emergencies necessitates using various specialized simulators for prediction, including earthquake propagation, safe evacuation route planning, etc. However, there is no common vocabulary nor standardized approach for integrating diverse building simulation models, hindering their direct integration in an unified collaborative simulation. This is a crucial limitation because no single simulator alone can accurately predict evacuation scenarios in the building industry. We propose the concept of Building Simulation Identity Cards (BSIC) that characterizes and integrates properties of specialized simulation models and demonstrates its role in collaborative simulations for emergency evacuation.

Keywords: Collaborative Simulations, Building Simulation Identity Cards, BIM, Emergency Evacuation

Introduction

Disasters, whether resulting from human activities or natural phenomena, pose a significant risk to life and property, even when they can be anticipated. Emergency evacuation, as a primary safety measure, involves the organized movement of people from disaster areas to safe zones. This practice has been extensively studied and implemented to mitigate the devastating consequences of such events (Yueming & Deyun, 2008).

Emergency evacuation simulations in buildings involve technological innovation, safety engineering, and collaborative planning. As our urban landscapes continue to expand and undergo transformation, safety and resilience in built environments become increasingly important. Research in the field of effective emergency evacuation gained momentum in the 1980s after nuclear incidents at Three Mile Island and Chernobyl (Battegazzorre et al., 2021; Johnson Jr & Zeigler, 1986). These incidents served as evidence of the inability of many emergency authorities to handle such catastrophic events. The subsequent development of specialized simulators has become indispensable for forecasting evacuation scenarios, encapsulating essential information such as geometry, behavior, occupant characteristics, environmental conditions, assessment of structural integrity under seismic conditions, identification of potential challenges through physical simulations, and estimation of evacuation time, among others.

However, despite the availability of powerful, specialized simulators, there is not a single simulator that can account for the highly diverse range of scenarios that users may need to make predictions about. For example, consider a prediction scenario for an earthquake event. An evacuation planning simulator alone often does not consider elements such as structural failure resulting from earthquake loading or considerations of lighting, electricity, weather, and time of day.

In response to these challenges, our study selectively focuses on specific simulations, including: (a) earthquake propagation within the building, (b) development of secure evacuation routes, (c) geometric modeling of the building structure, (d) assessment of structural integrity of the building under seismic conditions, (e) identification of potential challenges in evacuation through physical simulations, (f) estimation of evacuation time, and (g) analysis of occupant movement pattern to ensure the effectiveness of results.

Addressing the aforementioned challenge involves integrating specialized simulators effectively within a collaborative simulation, or so-called co-sim (Gomes, Thule, Broman, et al., 2018; Hansen et al., 2024; Thule et al., 2019) framework to ensure the validity, reliability, and formal verifiability of co-simulation results.

Toward achieving a comprehensive solution, our study introduces a novel concept, the Building Simulation Identity Cards (BSIC) which is aimed at addressing inconsistencies during the integration of simulation models, ensuring that different modules or components can interact correctly, proposed as a comprehensive research agenda and vision for the community. In this paper, we will introduce and outline the development of the BSIC concept, drawing inspiration from key technological initiatives in other industries such as manufacturing, automobile, and aviation, where similar approaches have proven successful in enhancing operational efficiency and interoperability between simulation models.

The process for the development of BSIC involves the creation of standardized ontologies and meta-models to characterize building simulators, which will incorporate available information regarding the simulation model across various aspect (Aßmann et al., 2006; Mahdavi et al., 2023). It involves creating standardized interfaces, frameworks, and algorithms to facilitate their integration into collaborative simulations (Hansen et al., 2022) . An example of this approach is the Model Identity Card (MIC) that has been developed for characterizing simulators in the automotive industry (Sirin et al., 2015).

Attached to the emergency evacuation planning domain, The BSIC concept will incorporate Functional Mockup Interface (FMI) (Schwan et al., 2017) and co-simulation theory and frameworks. This ensures the standardized storage and sharing of simulation model information, including interfaces, input/output parameters, methods, and usage data. This integration will enhance collaboration and knowledge transfer between simulation models, promoting interoperability and mitigating existing barriers.

BSIC will serve as a novel BIM-based solution for harmonizing the properties and attributes of various simulation models employed in the context of emergency evacuation. BSICs act as standardized profiles for simulation models integrated with BIM standards (Eastman, 2011). In this framework, the present study will address the following research question:

RQ: How can the integration of two independent simulation models be systematically achieved to facilitate the co-simulation process in the building sector for emergency evacuation planning in case of earthquake?

By leveraging BSIC, we have a potential avenue for improved collaboration and communication among stakeholders, researchers, and practitioners involved in emergency evacuation simulations. In this paper, we introduce the concept of BSIC as a solution to the challenge of the integration of specialized simulators including earthquake analysis and emergency evacuation simulator for predictive simulations in case of emergency evacuation planning from buildings.

Related Work

There are several research studies focused on emergency evacuation simulation within buildings. (Gelenbe & Desmet, 2013) used graph theory to identify critical positions for emergency evacuations in buildings. In another study. (Forssberg et al., 2019) aimed to improve the reliability of evacuation design assessments by analyzing the variability in pre-movement times during building evacuations. (Mirahadi & McCabe, 2021) proposed the utilization of Dijkstra's algorithm to identify the most secure path-planning strategy for evacuations, particularly in the context of fire emergencies. The model establishes a risk factor for each compartment, taking into account factors such as fire location and potential blockages. By employing a modified version of Dijkstra's algorithm, the model calculates the path with the lowest risk. (Kirby et al., 2015) in their study, they used AnyLogic software to create an evacuation simulation model, demonstrating the importance of data on optimal staff, materials, space, and time resources required for evacuation planning. Additionally, (Chu et al., 2019) in their study investigated the emergency evacuation simulation and management optimization in urban residential communities. A framework was developed for data acquisition, scenario development, evacuation simulation, and emergency management analysis.

In parallel, collaborative simulations (co-sim) have emerged as a topic of increasing interest in the building industry. (Alfalouji et al., 2023) investigated the integration of multiple tools for co-simulation of buildings and smart energy systems. This method has significant potential in advancing building envelopes due to its ability to accommodate complex control strategies and sequences.

Framework for co-simulations for building

By pursuing our aim in this paper, the Building Simulation Identity Card (BSIC) concept is developed to overcome challenges in integrating and orchestrating specialized simulators in a collaborative simulation framework. In this light, we propose a roadmap for BSIC development inspired by major technological initiatives, i.e MIC, to characterize simulators in the automotive industry.

In order to address occupant safety challenges in buildings, a design and engineering team develops a comprehensive digital model of the building, very often incorporating BIM-based programs such as Revit. Subsequently, the structural engineer analyzes the building for potential failure and risk under earthquake loading (Smith, 2016) using the BIM model in a structural integrity simulator. The earthquake loading is sourced from another plateform, e.g., PEER Ground motion data base (PEER-Center, 2013). The data from this simulator needs to be integrated into the evacuation planning simulator. The data may include information about the occupants, output from the structural integrity simulator, and available evacuation routes. Taken together, the purpose of conducting these simulations is to plan the evacuation of people from the building in the event of an earthquake. Yet, neither of the two aforementioned simulators can independently execute such a scenario. Therefore, running a co-simulation is imperative to obtain the desired results. However, the lack of a common vocabulary for integrating different simulators poses a high risk of simulation model integration failure. The framework for co-simulations for emergency evacuation planning from buildings is represented in Figure 1. The evacuation planning engineer uses BSIC to gather the structural integrity simulator output, which serves as input for the emergency evacuation simulator. This process involves manual implementation, where a structural engineer formulates the BSIC for the structural integrity simulator. Subsequently, an evacuation planning engineer utilizes this BSIC as input for the emergency evacuation simulator.

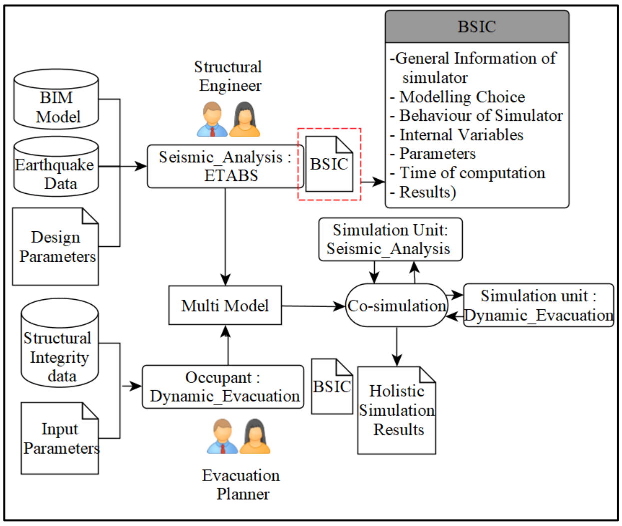


Figure 1: Framework for co-simulations for emergency evacuation from buildings.

In co-simulation, the process begins by defining the connections between simulation unit instances at the system modeling level. These simulation units interact through designated interfaces, known as ports. For instance, in the seismic analysis and dynamic evacuation simulation unit, there is a float output port. The framework also incorporates the Functional mockup interface (FMI) (Palmieri et al., 2020), a common interface standard crucial for co-simulation. FMI provides a standardized approach for encapsulating simulation functionalities, enabling seamless transfer of inputs between simulation units. In assosiation with Functional mockup units (FMUs), which are standardized models for exchanging simulation data, multi-model facilitates the transfer of input to each simulation unit at the current time step. Subsequently, within each simulation unit, the time step for the next major iteration is calculated and used in the multi-model (see next sectoin for multi-model). Each simulation unit advances in a time step until it reaches the point where the maximum shear and moment causing structural failure of the beam are obtained. A collaborative simulation using this multi-model is finally executed by a Co-sim Orchestration Engine (COE), which will act as the central control unit, coordinating interactions among simulation instances. This process is done manually as a part of proof of concept.

Building Simulation Identity Card (BSIC)

We develop BSIC that represents key attributes of simulation models, including general information about the simulator, modeling choices, its behaviour, internal variables, parameters, and simulation results, which serve as the basis for input for other simulators. As presented in Table 1, these attributes are part of the proof-of-concept study, and a more detailed formalization of the BSIC will be undertaken in future research.

Table 1: Classification of attributes used to formulate BSIC.

Attributes	Description
Information	Name , Purpose, description, run time & version of simulation model
Modelling Choice	Modelling field, model dimension and time scale
Required Simulation tool	Name , version and alternative simulator tool
Behaviour	Behaviour specification, analysis type
Interface	Nature, domain , sub-domain
Internal Variables	Type, description, value, unit
Parameters	Classification, quantity, scale
Simulation Results	Time step, accuracy, outputs

Multi-model

FMUs and their interdependencies establish the framework known as a multi-model system. The concept of multi-modeling involves the integration of diverse simulation models to analyze complex systems (Fishwick et al., 1994). This enables communication among different simulators and provides information that cannot be obtained through the use of a single model. This approach allows for a more comprehensive analysis of the system's overall dependability and performance under various scenarios, such as emergency evacuation planning from buildings. For instance, in the context of emergency evacuation planning scenarios, multi-modelling allows the integration of structural integrity and emergency evacuation models. Each model represents a different aspect of the case, facilitating a more holistic understanding of the system as a whole.

In this study, we develop a multi-model that uses BSIC to aid in the solution of potential inconsistencies in the creation and combinations of specialized simulation models. Figure 2 shows the multi-model for co-simulation of emergency evacuation planning incorporating structural integrity.

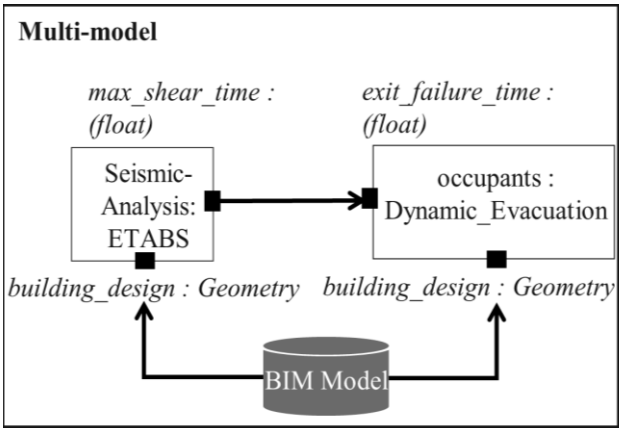


Figure 2: Emergency evacuation planning multi-model.

Proof of concept demonstration

In this section we present a proof-of-concept demonstration of an evacuation scenario that integrates an earthquake simulator and occupant egress simulator. The structure under examination is intended to be simple in terms of geometry, a single-story building featuring two rooms measuring 20 by 30 feet each. The building has been modelled using Autodesk Revit software. The structure has one normal exit, referred to as Evacuation Point (E.P)1, and an emergency exit labelled E.P2. The primary evacuation route is E.P1, which is used by most occupants during normal times. In case E.P1 is inaccessible, individuals will use E.P2 as an emergency exit. The total area of the building encompasses 1200 square feet, accommodating 20 individuals. Figure 3 represents the floor plan of the building.

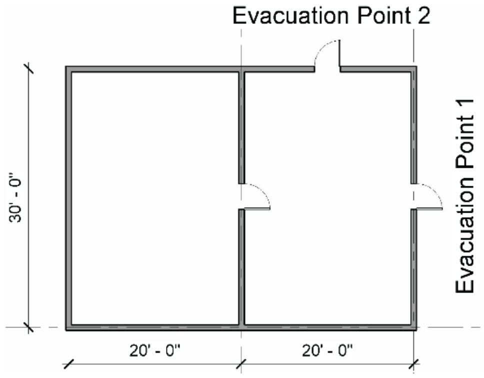


Figure 3: Building floor plan.

A comprehensive structural analysis of the building was conducted, revealing a fundamental time period (Çelebi, 2007) of 0.84 seconds. ETABS software was used for a comprehensive analysis of structural stability and earthquake impact (Guleria, 2014). The time history of the 1989 Loma Prieta earthquake (PEER-Center, 2013) served as a reference for this analysis. The structural analysis revealed the maximum stresses experienced by structural elements at t=5 sec, with corresponding shear and moment recorded. During this critical instance, the shear and moment data suggest a potential beam failure above E.P1. This is because the design shear and moment capacity of the beam is less than the shear and moment caused by the applied loads. Subsequently, these findings were transcribed into the BSIC (see the next section), forming the basis for input in an emergency evacuation analysis. To facilitate evacuation analysis, a dedicated agent-based simulator was employed using the Python language.

Results

The ETABS analysis provides critical information regarding the structure's seismic response. This is represented through a comprehensive time history plot, illustrating the dynamic movement of the structure's floors. The plot represents base shear over time, describing the structure's response to seismic forces. Figure 4 represents a time history plot illustrating the seismic response of the building under earthquake loading, indicating a peak base shear of -78 kips occurring at t = 5 seconds in X direction. This plot is utilized to analyze the behavior of the building under seismic loading (Rathod & Gupta, 2020).

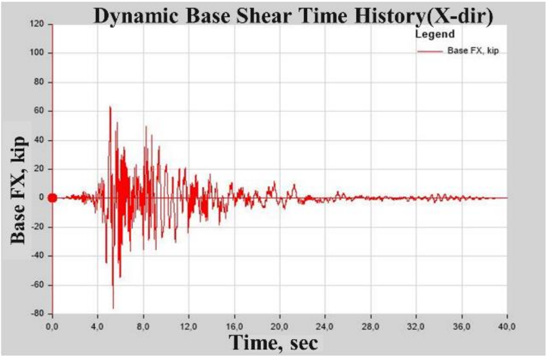
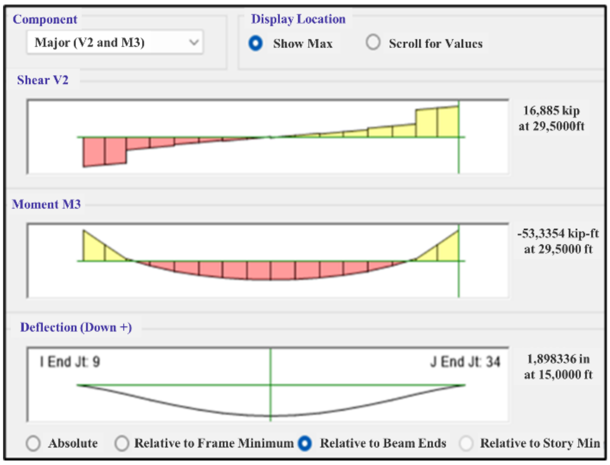


Figure 4: Dynamic base shear time history plot (X-dir) for the building under earthquake loading.

The analysis results indicate that at t = 5 seconds, the structural beam above E.P1 experience maximum stress. At this point, the stress level has reached a critical level, which indicates a potential vulnerability in the structure. It's important to note that the beam above E.P1 may fail due to a critical stress condition, leading to its blockage.


Component: Major (V2 and M3)

Display Location: ● Show Max ○ Scroll for Values

Shear V2: 16,885 kip at 29,5000ft

Moment M3: -53,3354 kip-ft at 29,5000 ft

Deflection (Down +): 1,898336 in at 15,0000 ft

○ Absolute ○ Relative to Frame Minimum ● Relative to Beam Ends ○ Relative to Story Min

Figure 5: Screenshot of the ETABS tool showing the maximum moment and shear diagram for beam above E.P1 at t=5 sec

The seismic forces during the earthquake event have created conditions where the moment and shear forces acting on the beam above E.P1 exceed its design structural capacity. This ultimately leads to beam failure. Figure 5 illustrates the moment and shear diagram for the beam under consideration subjected to earthquake loading. Figure 6 illustrates the lateral displacement of the structure in the X-dir, providing a visual representation of structural deformation under earthquake loading. The displacement in the X-dir is more than in the Y-dir. Notably, the lateral displacement of the structure at t=5 seconds exceeds the allowable limit of H/500 (Abd Samat et al., 2017), reaching 0.6 inch. This will cause structural failure starting from the beam above E.P1.

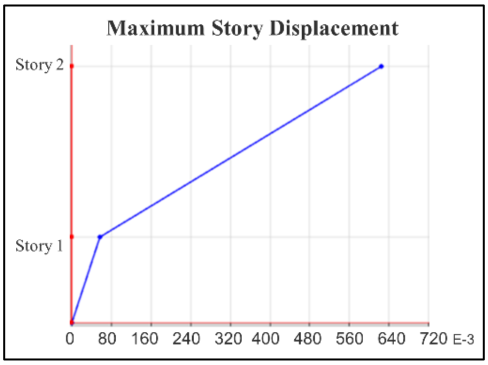


Figure 6: Lateral story displacement in X-direction.

The integration of outcomes derived from the seismic analysis simulator into the evacuation planning simulator has been executed manually, serving as a proof of concept. This process is represented in the sequential diagram illustrated in Figure 7. A master algorithm is utilized by a Co-sim Orchestration Engine (COE), such as the Jacobi algorithm, which performs a simulation step by initiating the advancement of all FMUs in time, retrieving the necessary outputs, and setting the necessary inputs (Gomes, Thule, Larsen, et al., 2018). The simulation follows a series of iterative steps until a termination condition is met, typically determined by the maximum timestep specified by the user. The procedural sequence can be described as follows: The COE initiates the simulation cycle by dispatching inputs to all FMUs. Subsequently, the COE retrieves the next time step from each FMU. Advancing the simulation, the COE progresses the state of each FMU's simulation to the minimum (earliest) time reported by the respective units. Finally, the COE consolidates the output data generated by all FMUs.

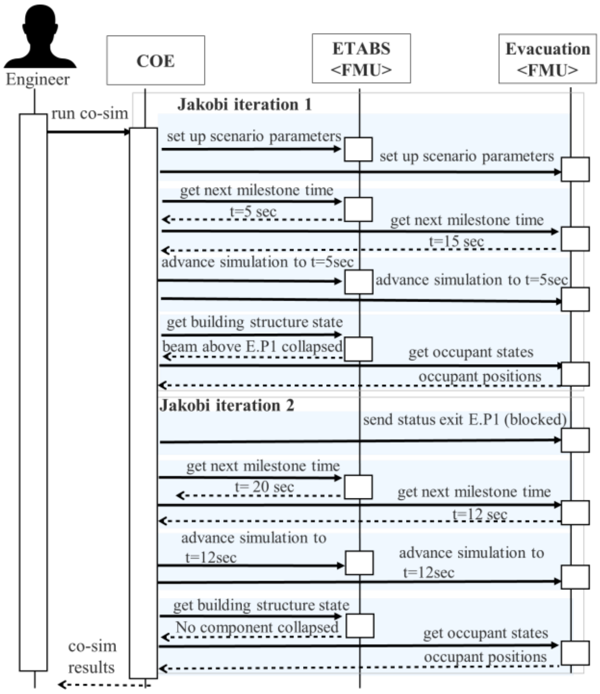


Figure 7: Sequence diagram for co-simulation in Emergency evacuation planning

BSIC used in co-sim process for structural integrity simulation is represented in Figure 8. It reflects a understanding of simulation model characteristics. It provides general information about the simulation model, such as its name, purpose, and the simulator employed for execution. Additionally, it covers details related to the modeling and behavior of the simulation model. The BSIC also encompasses variables and parameters that are necessary for the design of the simulation model. Finally, it presents the results obtained from the simulation model.

Subsequently, the BSIC information is then integrated into simulation model for evacuation analysis. The latter is executed by developing Python code that establishes a comprehensive and integrated approach. This approach will accommodate the seismic activity and emergency evacuation scenarios within our model.

SeismicAnalysis_ETABS	
Attributes	**Description**
General Information	
Name of Simulation Model	SeismicAnalysis_ETABS
Simulation purpose	Earthquake analysis
Description	This simulation model serves the purpose of providing information on the maximum stresses occurring at a specified time and location
Simulation run time	Varies based on the complexity of the model
Software/language used	ETABS (Extended Three-Dimensional Analysis of Building Systems)
File format name	.e2k, .edb, .f2k, .exr, .DXF/.DWG, CIS/2, IFC, .igs, .stl, .obj, .xlsx, .docx, .accdb
Modelling Choice	
Modelling Field	Structural Engineering
Model dimension	2 rooms (20x30x11)
Applied Earthquake	Loma Prietan1989
Time scale	Time-dependent analysis capturing seismic events
Behaviour	
Behaviour specification	Material nonlinearity, geometric nonlinearity, and boundary condition nonlinearity considered
Analysis type	Dynamic Time-History Analysis for seismic response
Internal Variables	
Time History	X and Y-direction
Base Shear X-direction	56Kips
Base Shear Y-direction	78Kips
Damping	0.5%
Parameters	
Spectral Acceleration (X-dir)	0.78g
Spectral Acceleration (Y-dir)	0.75g
Concrete compressive strength	4000psi
Poission´s ratio	0.2
Results	
Time of max response	5 sec
Fundamental time period	0.82sec
Design moment	-52kips-ft(top), 27kip-ft(bottom)
Shear capacity	11.95kip
Moment at beam due to E.Q loading	-53-3kip-ft
Moment at beam due to E.Q loading	16.9 kip
Lateral displacement (allowable H/500)	0.26 in
Lateral displacement at E.Q loading (X-dir)	0.6inch
Lateral displacement at E.Q loading (Y-dir)	0.57inch

Figure 8: BSIC for structural integrity simulator

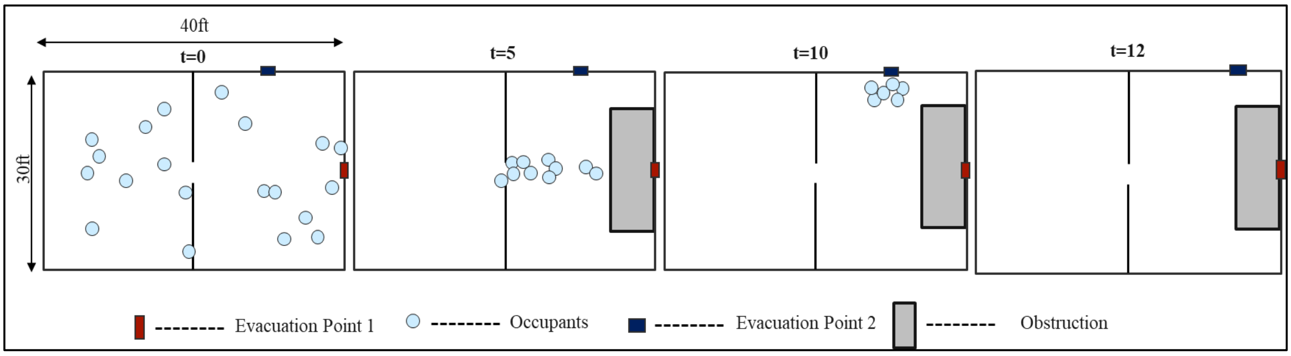


Figure 9: Emergency evacuation scenario w.r.t time.

Agent-based simulation is employed to predict the evacuation of people within the building during a seismic event. Figure 9 illustrates thse flow of people towards the primary exit, also known as E.P1, at times t = 0 and t = 5 sec. However, in the event of a structural failure occurring at evacuation point 1 at time t = 5 sec, the primary exit becomes obstructed by rubble. As a result, people will move towards E.P2, identified as the secondary exit. The figure illustrates that at t = 12 sec, all the occupants have evacuated the building safely.

The dynamics of the evacuation rate, as derived from the data collected during the evacuation simulation, are depicted in Figure 10. Notably, the rate of evacuation increases significantly when a large number of people are at an evacuation point at the same time. In the observed time frame from t = 0 to t = 5 seconds, there is a noticeable upward trend in the cumulative departure of occupants from the building.

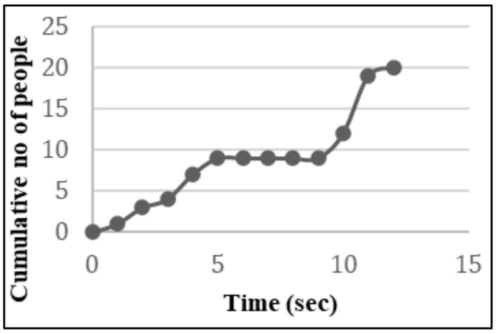


Figure 10: Cumulative number of people leaving the building.

Conversely, between t = 5 seconds and t = 9 seconds, a consistent evacuation rate is observed. This stabilization corresponds to occupants redirecting their movement towards E.P2 following the closure of E.P1. At t=12 seconds, where the graph reaches its peak, all 20 occupants have noticeably vacated the room.

Figure 11 represents the concise BSIC version of the dynamic evacuation simulation model, summarizing crucial information about the simulator used, its inputs, and outputs. It provides a comprehensive understanding of the simulation process, including different attributes of simulation model. This BSIC will prove valuable in the iterative development of the structural integrity simulator and in designing additional simulation models for co-simulation purposes.

BSIC: Dynamic_Evacuation	
Attributes	**Description**
General Information	
Name of Simulation Model	Dynamic_Evacuation
Simulation purpose	Emergency evacuation
Description	The simulation models the movement of people towards evacuation points considering room structures and obstacles.
Simulation run time	20 seconds
Software/language used	Python
Modelling Choice	
Modelling Field	Evacuation Planning
Model dimension	2 rooms (20x30)
Time scale	Discrete
Behaviour	
Behaviour specification	Individuals exhibit dynamic movement, responding to room structures and obstacles, with a focus on reaching evacuation points.
Analysis type	Real-time Visualization
Evacuation Strategy	Dynamic pathfinding based on real-time structural information.
Internal Variables	
Description	Instances representing individuals spped and obstacles in the simulation
No of structural component failure	1
Speed of occupants	3ft/s
Parameters	
Name	Room width, room length, no people, speed, total time
Description	Parameters defining the simulation environment, evacuation points, number of people, and speed
No. of occupants	20
No. of evacuation points	2
Model dimension	2 rooms (20x30x11)
Results	
Time step	1 sec
Time of structural failure	5 sec
Evacuation Success Rate	100%
Total evacuation time	12 sec

Figure 11: BSIC for emergency evacuation simulator

Discussion

To address the issues related to the combination of a specialized simulation model for information storage and sharing, we demonstrated the first proof of concept of BSIC. For conducting emergency evacuation simulations from a building in case of an earthquake, the provided proof of concept serves as a foundational framework for co-simulations. To improve emergency evacuation planning, integrating data from diverse simulations is imperative, e.g., understanding earthquake propagation, managing dynamic crowd flows during egress, and creating building structure models are crucial components. Furthermore, emergency evacuation planning should consider assessing structural integrity during earthquakes, estimating evacuation time to prevent injuries and analyzing occupant movement patterns.

In this study, we used a seismic analysis simulator to determine if the structure would fail during an evacuation due to earthquake loading. Then the data from the seismic analysis simulation model is integrated with an evacuation planning simulation model to understand the significance and usability of BSIC in combining diverse simulation models.

The integration process between simulation models is executed manually, creating the challenge of automating the co-simulation process, which needs consideration. This includes the implementation of ETABS and the dynamic evacuation simulator as proper FMUs integrated into a COE, and the processing of inputs and outputs for seamless communication between the two simulators. An intricate issue in automating the process concerns the sequential aspects of simulation data. The ETABS simulator focuses on the structural time scale, whereas the dynamic evacuation simulator focuses on crowd behavior dynamics. Future studies will focus on running this co-simulation process automatically.

Furthermore, the integration between specialized simulation models not only highlights the interaction between seismic analysis and the evacuation planning simulation model but also emphasizes the practical application of BSIC in enhancing the understanding of the emergency evacuation planning process.

BSIC outlined in Figure 8 and Figure 11 represents a limited understanding of Seismic analysis and evacuation planning simulation model properties. BSIC is used for classifying analysis modelling, including input/output parameters and quality expectations. A comprehensive BSIC at full scale will be developed in a future study.

Conclusion

Our study, focused on improving collaboration and integration among simulators for predictive simulation during emergency evacuation planning from buildings in earthquake scenarios, has yielded significant insights into co-simulation complexities. The efforts were put in place to answer the research question projected in the introduction.

We first introduced and configured the concept of BSIC to facilitate the co-simulation process for independent simulation models. Then, we utilized BSIC for integrating specialized simulators into emergency evacuation prediction scenarios. Our study achieved significant progress by surpassing the limitations of individual simulators through the successful implementation of a standardized and shared vocabulary.

We implemented BSIC in emergency evacuation predictions by standardizing model representation, ensuring an accurate representation of various factors from both seismic analysis and emergency evacuation simulation models.

This addresses challenges related to a lack of common terminology and interface inconsistencies during the integration phase of a simulation model, whether performed manually or facilitated by software. Through standardized interfaces and frameworks, BSIC facilitates informed decision-making for design teams, enabling effective collaboration in the integration of seismic analysis and evacuation planning simulators.

This research lays the foundation for future investigations, where we aim to further consolidate data from various simulation models, building upon the capabilities of BSIC to achieve a comprehensive understanding of the emergency evacuation planning process. In this regard, BIM will play a crucial role in emergency evacuation planning by facilitating realistic scenario modeling, aiding in the planning of evacuation routes, assessing potential damage, and effectively allocating resources (Stančík et al., 2018). BIM's ability to create a digital replica of real-world structures and environments, complete with intricate details, provides a strong foundation for disaster preparedness. In the next stage, our project focuses on how and in which way integration of BIM with specialized building simulators should be developed to use extensive datasets, offering insights into complex details related to structural integrity and evacuation planning.

References

Abd Samat, R., Chua, F. T., Mustakim, N. A. H. M., Anuar, F. I., Saad, S., & Bakar, S. A. (2017). Lateral Displacement And Shear Lag Effect Of High-Rise Buildings With Diagrid SystemThat Is Constructed Above A Frame. MATEC Web of Conferences,

Alfalouji, Q., Schranz, T., Falay, B., Wilfling, S., Exenberger, J., Mattausch, T., Gomes, C., & Schweiger, G. (2023). Co-simulation for buildings and smart energy systems — A taxonomic review. Simulation Modelling Practice and Theory, 126, 102770. https://doi.org/https://doi.org/10.1016/j.simpat.2023.102770

Aßmann, U., Zschaler, S., & Wagner, G. (2006). Ontologies, Meta-models, and the Model-Driven Paradigm. In C. Calero, F. Ruiz, & M. Piattini (Eds.), Ontologies for Software Engineering and Software Technology (pp. 249-273). Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-34518-3_9

Battegazzorre, E., Bottino, A., Domaneschi, M., & Cimellaro, G. P. (2021). IdealCity: A hybrid approach to seismic evacuation modeling. Advances in Engineering Software, 153, 102956.

Çelebi, M. (2007). On the variation of fundamental frequency (period) of an undamaged building–a continuing discussion. International Conference on

Experimental Vibration Analysis for Civil Engineering Structures. Porto,

Chu, H., Yu, J., Wen, J., Yi, M., & Chen, Y. (2019). Emergency Evacuation Simulation and Management Optimization in Urban Residential Communities. Sustainability, 11(3), 795. https://www.mdpi.com/2071-1050/11/3/795

Eastman, C. M. (2011). BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors. John Wiley & Sons.

Fishwick, P., Narayanan, N., Sticklen, J., & Bonarini, A. (1994). A Multi-Model Approach to Reasoning and Simulation. Systems, Man and Cybernetics, IEEE Transactions on, 24, 1433-1449. https://doi.org/10.1109/21.310527

Forssberg, M., Kjellström, J., Frantzich, H., Mossberg, A., & Nilsson, D. (2019). The Variation of Pre-movement Time in Building Evacuation. Fire Technology, 55(6), 2491-2513. https://doi.org/10.1007/s10694-019-00881-1

Gelenbe, E., & Desmet, A. (2013). Graph and Analytical Models for Emergency Evacuation. Future Internet, 5. https://doi.org/10.3390/fi5010046

Gomes, C., Thule, C., Broman, D., Larsen, P. G., & Vangheluwe, H. (2018). Co-simulation: a survey. ACM Computing Surveys (CSUR), 51(3), 1-33.

Gomes, C., Thule, C., Larsen, P. G., Denil, J., & Vangheluwe, H. (2018). Co-simulation of continuous systems: a tutorial. arXiv preprint arXiv:1809.08463.

Guleria, A. (2014). Structural analysis of a multi-storeyed building using ETABS for different plan configurations. Int. J. Eng. Res. Technol, 3(5), 1481-1485.

Hansen, S. T., Thule, C., Gomes, C., Lausdahl, K. G., Madsen, F. P., Abbiati, G., & Larsen, P. G. (2024). Co-simulation at different levels of expertise with Maestro2. Journal of Systems and Software, 209, 111905. https://doi.org/https://doi.org/10.1016/j.jss.2023.111905

Hansen, S. T., Thule, C., Gomes, C., van de Pol, J., Palmieri, M., Inci, E. O., Madsen, F., Alfonso, J., Castellanos, J. Á., & Rodriguez, J. M. (2022). Verification and synthesis of co-simulation algorithms subject to algebraic loops and adaptive steps. International Journal on Software Tools for Technology Transfer, 24(6), 999-1024. https://doi.org/10.1007/s10009-022-00686-8

Johnson Jr, J., & Zeigler, D. J. (1986). Modelling evacuation behavior during the Three Mile Island reactor crisis. Socio-Economic Planning Sciences, 20(3), 165-171.

Kirby, A. M., Dietz, J. E., Matson, E. T., Pekny, J. F., & Wojtalewicz, C. (2015). Major city evacuation planning using simulation modeling. International Journal of Disaster Resilience in the Built Environment, 6(4), 397-408.

Mahdavi, A., Wolosiuk, D., & Berger, C. (2023). Toward a theory-driven ontological framework for the representation of inhabitants in building performance computing. Journal of Building Engineering, 73, 106804. https://doi.org/https://doi.org/10.1016/j.jobe.2023.106804

Mirahadi, F., & McCabe, B. Y. (2021). EvacuSafe: A real-time model for building evacuation based on Dijkstra's algorithm. Journal of Building Engineering, 34, 101687. https://doi.org/https://doi.org/10.1016/j.jobe.2020.101687

Palmieri, M., Bernardeschi, C., & Masci, P. (2020). A framework for FMI-based co-simulation of human–machine interfaces. Software and Systems Modeling, 19(3), 601-623.

PEER-Center. (2013). PEER Ground Motion Database. https://ngawest2.berkeley.edu/

Rathod, K. V., & Gupta, S. (2020). A nonlinear time history analysis of ten storey RCC building. International Research Journal of Engineering and Technology, 7, 7153-7160.

Schwan, T., Unger, R., & Pipiorke, J. (2017). Aspects of FMI in Building Simulation. Modelica,

Sirin, G., Paredis, C. J., Yannou, B., Coatanéa, E., & Landel, E. (2015). A model identity card to support simulation model development process in a collaborative multidisciplinary design environment. IEEE Systems Journal, 9(4), 1151-1162.

Smith, P. (2016). Structural design of buildings. John Wiley & Sons.

Stančík, A., Macháček, R., & Horák, J. (2018). Using BIM model for Fire Emergency Evacuation Plan. MATEC Web of Conferences, 146, 01012. https://doi.org/10.1051/matecconf/201814601012

Thule, C., Lausdahl, K., Gomes, C., Meisl, G., & Larsen, P. G. (2019). Maestro: the INTO-CPS co-simulation framework. Simulation Modelling Practice and Theory, 92, 45-61.

Yueming, C., & Deyun, X. (2008). Emergency evacuation model and algorithms. Journal of Transportation systems engineering and information technology, 8(6), 96-100.