A Multi-Layer Navigation Approach for Interactive Pedestrian Flow Simulation in Digital Twins

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Abstract: Pedestrian flow simulation is crucial for accurately depicting daily activities and dynamics of infrastructures, such as town halls, train stations, or airports. Current pedestrian flow models often lack the capability to interact with environmental changes in real-time or only focus on one-directional interactions via prescribed events. To address this limitation, we propose a hybrid approach that combines graph-based methods for large-scale navigation with the optimal steps model for small-scale navigation and locomotion of agents. This combination enables dynamic updates according to environmental changes provided by other simulations. We demonstrate the effectiveness of our proposed approach in an exemplary airport architecture where pedestrian simulation is coupled with an electrical simulation, resulting in a successful bidirectional coupling. Specifically, we consider a scenario where a saboteur agent meddles with an electrical circuit, causing a ripple effect that impacts pedestrian behavior.

1 INTRODUCTION

In recent years, the concept of digital twins has become increasingly significant across various fields, offering a new approach to understand and interact with complex systems. Essentially, a digital twin serves as a virtual replica of a physical entity or system, providing a dynamic and immersive reflection of its real-world counterpart (Grieves, 2015). This connection between the physical and digital realms has opened up new possibilities for exploration and innovation in diverse sectors with applications in healthcare, urban planning, manufacturing, and infrastructure (Thelen et al., 2022).

As pedestrian dynamics are an important part of the operation of different infrastructures, the demand for computationally efficient pedestrian flow simulations has grown in digital twins. Understanding human behavior and their interaction with technical systems is vital for optimizing infrastructure operation. Moreover, forecasting the impact of incidents on infrastructure operation is essential to evaluate contingency plans and to develop concepts for infrastructure protection.

Current state-of-the-art tools enable us to simulate and analyze complex phenomena with a high level of accuracy and detail using prescribed events impacting the simulation. However, there are no tools available that allow direct real-time bidirectional coupling with other simulations and/or sensors or actuators, and few works have been published on that topic. However, pedestrian behavior is influenced by various environmental factors, including pathway accessibility, awareness of available routes, weather conditions, and more. Many of these factors can be effectively modeled and predicted using established simulation techniques. Integrating these simulations within a comprehensive digital twin of a socio-technical system provides deeper insights into the dynamics of pedestrian movement.

Imagine a scenario where a pedestrian simulation interacts with an electrical simulation to model the connection between human movement and building infrastructure. As an employee enters a conference room, their presence activates an occupancy sensor, adjusting lighting, heating, ventilation, and security settings for energy efficiency and comfort. However, maintenance staff or malicious actors who interact with power boxes can disrupt the system, impacting not only lighting but also security mechanisms and pedestrian flow. This includes electrical door failures that can create bottlenecks and alter evacuation

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routes.

The tight integration between the pedestrian simulation and the electrical simulation opens up new ways of forecasting the system's behavior under unforeseen conditions. By dynamically updating the navigation model based on environmental changes, the digital twin ensures optimal pedestrian flow and accessibility, contributing to the overall resilience and operational performance of the building.

To achieve acceptable computation times, while being able to update the navigational model throughout the simulation, we propose a two-layer navigation model with a microscopic navigation based on a variation of floor field cellular automata and a graph-based macroscopic navigation similar to the works of Kneidl et al. (2013). By cutting the floor fields based on the rooms of the architecture at hand, we reduce the amount of necessary computations. By dynamically updating the navigation graph at run time, we allow for reacting to environmental changes in real-time.

This paper is structured as follows: Section 2 provides a brief overview of pedestrian simulation and highlights studies that explore its coupling with other simulators. Section 3 outlines the models employed for each navigation layer and offers a detailed explanation of the agent's navigation process within the simulation. Additionally, it describes the interaction framework and data model used to couple simulations. Section 4 presents the simulation example, detailing the pedestrian simulation setup, including geometry and parameter values, and introducing the electrical simulator as the coupled counterpart. The results of the corresponding simulation are presented in Section 5, followed by a discussion of current limitations and potential future improvements in Section 6.

2 RELATED WORK

Previous studies incorporating agent-based pedestrian simulation into digital twins have primarily focused on traffic interactions (Wang et al., 2023), crowd behavior (White et al., 2021), and emergency evacuation scenarios (Han et al., 2020; Umemoto et al., 2024). These implementations often rely on fundamental models such as cellular automata or social force models. Cellular automata represent pedestrian movement on a discrete grid, where agents transition between cells based on predefined local rules, making them computationally efficient but sometimes limited in realism. In contrast, social force models treat pedestrians as particles influenced by attractive and repulsive forces, capturing continuous movement dynamics and interactions with obstacles or other agents. The optimal steps model (Köster et al., 2011) bridges the gap between social force models and cellular automata by allowing pedestrians to move on a continuous plane while using a floor-field-based cellular automata approach to find the optimal stepping position.

Other pedestrian movement models aim to enhance realism by incorporating microscopic behavior and strategic decision-making. These approaches not only refine small-scale interactions, such as steering around congestion, but also integrate high-level path planning (Seitz and Köster, 2012; Kneidl et al., 2013; Asano et al., 2010). Some of these models use graph-based navigation with A*-based algorithms (Hart et al., 1968). Such methods are widely applied in areas like computer games, where they enable the adaptive movement of non-player characters (Cui and Shi, 2011).

While bidirectional coupling between pedestrian simulation and other systems remains an underexplored area, a few studies have begun to investigate this approach. One example couples the Simulation of Urban MObility (SUMO) with the Unity3D game engine to study the interaction between pedestrians and connected vehicles (Artal-Villa and Olaverri-Monreal, 2019). This coupling allows for real-time interaction and provides a more dynamic understanding of pedestrian behavior in relation to traffic systems. Another study builds on this by using the CARLA-SUMO co-simulation framework, integrating it with the CAVE Automated Virtual Environment (CAVE) to allow users to interact with the simulation (Wang et al., 2023). A third study couples SUMO (Simulation of Urban Mobility) and Vadere with OMNeT++ to co-simulate pedestrian movement alongside telecommunications network behavior (Schuhbäck et al., 2019). This integration enables an analysis of how pedestrian behavior might impact or be impacted by communication infrastructure, albeit with a limitation: the use of discrete-event simulation in OMNeT++ requires that the pedestrian simulation be restarted with new starting conditions for every event-based change in the telecommunications network, which restricts real-time coupling. Despite these promising efforts, research in this area remains sparse, with these three studies among the very few addressing such bidirectional coupling.

3 METHODS

For small-scale navigation, we use the optimal steps model (Seitz and Köster, 2012), which is based on

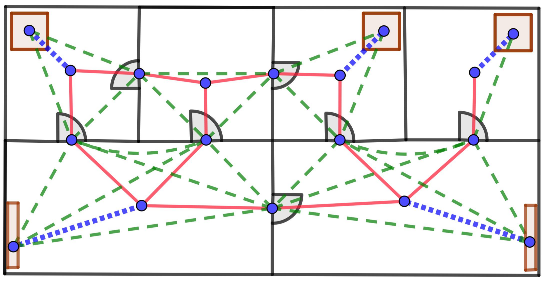


Figure 1: The black outline depicts the geometry of the building, as extracted from the floor plan. The brown areas are target areas, added subsequently. Differently colored vertices and edges describe the different steps of the construction of the navigation graph.

the fact that pedestrians naturally move in a discrete way, step-by-step. On the larger scale, our navigation graph cuts the underlying geometry of the building into different sections that are separated by doors. These separate rooms serve as the natural boundaries for the calculation of the floor fields used on the microscopic layer. This approach significantly reduces the computational time required for computing floor fields of pedestrian destinations. For many buildings these structural graphs are tree-shaped, but for more complex buildings such as train stations, airports or town halls, these graphs can include circular features with the possibility to cross different rooms to get to the same destination.

To elucidate the individual steps of our approach in detail, we utilize a simplified example geometry, illustrated in Fig. 1. The geometry represents a small building composed of four rooms with dimensions of approximately 4.5 meters by 4 meters, and two hallways of similar size (4.5 meters by 8 meters) connected by doors with widths of around 1 meter. The walls are represented by black lines, while door areas are shaded in gray. Three of the rooms have designated target areas that function as pedestrian destinations (note the three brown rectangles within the upper rooms in Fig. 1). Inside the bottom left hallway, we have an entrance area, and inside the bottom right hallway, there is an exit area, depicted as rectangles shaded in brown.

3.1 The Optimal Steps Model

The optimal steps model combines the advantages of different approaches to model pedestrian movement, namely cellular automata and social force models. Building upon the cellular automata approach of (Köster et al., 2011), the optimal steps model uses repulsive potentials of other pedestrians and obstacles and travel times to their target destinations to create

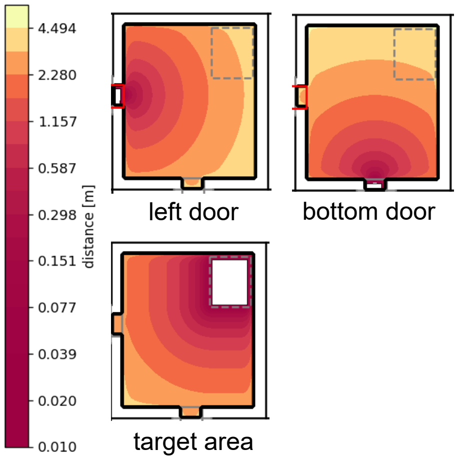


Figure 2: Navigation fields for the different points of interest, i.e. doors and target areas, within the middle-right upper room of our test geometry from Fig. 1.

a floor field and later on chooses the optimal step for each agent. These two phases are referred to as navigation and locomotion.

3.1.1 Navigation

The floor fields are created as scalar fields representing the travel times of a wavefront traversing from a destination through the room of the building at a certain speed that can be adjusted based on the distance to walls and other obstacles, to which pedestrians naturally try to keep a distance. Given there are no obstacles on the way, the value of the floor field will linearly match the Euclidean distance to the destination. The propagation of the wave can be described by the Eikonal equation:

$$V(\vec{x}) \cdot |\vec{\nabla} N(\vec{x})| = 1, \; N(\vec{x}) = 0 \text{ for } \vec{x} \in Z \tag{1}$$

where $V(\vec{x}))$ is the velocity field and $N(\vec{x})$ is the travel time to position $\vec{x}$ of the wave starting at target area Z.

$$V(\vec{x}) = \begin{cases} 0, & \vec{x} \in E \\ \min(1, \delta_E(\vec{x}) \cdot \frac{1}{d_c}), & \vec{x} \notin E \end{cases} \tag{2}$$

E denotes the area covered by walls and obstacles and $\delta_E(\vec{x})$ is the distance between position $\vec{x}$ and the closest obstacle. The wave cannot pass through walls and obstacles and the speed of the wave linearly increases from 0 to 1 within a certain distance d_c from these. If the distance is higher than d_c, the wave travels at a constant speed of 1.

We use the fast marching method (Sethian, 1996) as implemented in *scikit-fmm*[1] to solve the Eikonal equation and compute these floor fields efficiently.

[1]scikit-fmm: the fast marching method for Python, https://github.com/scikit-fmm/scikit-fmm

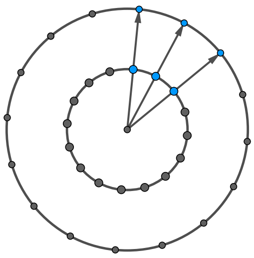


Figure 3: Discretization of the circles reflected by points. The three arrows represent six possible positions for the next step.

The set of three floor fields, two for the doors, one for the target area, within the middle-right upper room is shown in Fig. 2.

3.1.2 Locomotion

To find the optimal next step, the repulsive potential of agents in close proximity are considered in addition to the value of the floor field.

$$P_l(\vec{x}) = P_t(\vec{x}) + \sum_{i=1, i \neq l}^{n} P_{p,i}(\vec{x}) + \sum_{j=1}^{m} P_{o,j}(\vec{x}) \quad (3)$$

$P_t(\vec{x})$ is the attractive potential of the target t evaluated at position $\vec{x}$. $P_{p,i}(\vec{x})$ is the repulsive potential of pedestrian i and $P_{o,j}(\vec{x})$ the repulsive potential of obstacle j, affecting a pedestrian at position $\vec{x}$.

In contrast to a cellular automaton, this model uses local optimization on one or more circles around each pedestrian, taking into account a discrete number of positions (as shown in Fig. 3), while maintaining movement on a continuous plane by shifting the orientation of the circle between steps. $-P$ is evaluated as a utility function on positions along the discretized circle and the original starting position to determine the optimal next step. In our implementation we use two circles representing a large step and a small step (half-distance) and evaluate a total of 32 different positions per step.

3.2 The Navigation Graph

The construction process of the navigation graph is divided into three steps. First, we generate a floor graph consisting of the rooms and doors of the building as vertices. An edge between a door-vertex and a room-vertex exists exactly when the door is part of one of the boundary walls of the corresponding room. This is the case when a room has a door to the system boundary or the door connects two rooms with each other. This graph can be obtained from the building's geometry, for example, by using computer vision techniques on existing floor plans. This way we obtain the red graph in Fig. 1.

Second, we add vertices and edges that represent areas in which pedestrians take part in certain processes, such as queuing up for a ticket purchase or sitting down waiting for a train to arrive. Each of these areas is represented by a vertex as they are possible destinations for pedestrians. We then add an edge between these vertices and the room-vertex representing the room they are located in. These are the blue dotted edges in Fig. 1.

Finally, we remove all the vertices representing a room and add edges between each pair of each of their neighbors since those are arbitrarily set and not immediately relevant for the navigation of the pedestrians. We end up with a graph whose vertices are either possible pedestrians' destinations or doors they have to pass through to navigate between destinations.

In our example, this is the graph consisting of the orange and blue vertices connected by the green dashed edges. As edge weights of our graph, we use the travel times used in the optimal steps model.

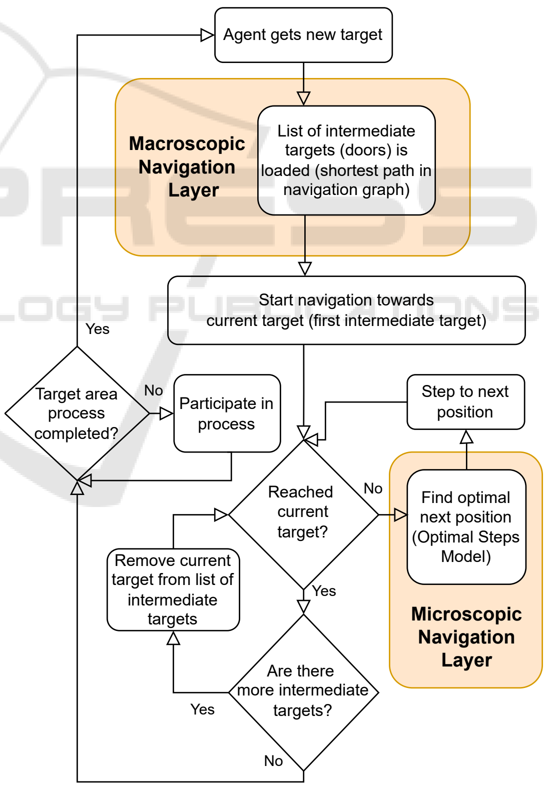


Figure 4: This flowchart diagram illustrates the complete navigation process of an agent, from target assignment to the calculation and execution of individual movement steps. The two layers of navigation are highlighted in orange boxes.

3.3 Pedestrian Routing

The model uses a destination-based routing, i.e., when an agent is created within the simulation, they are assigned a target area. Agents proceed to navigate towards this target until they reach it. Once the agent reaches their destination, they might spend a certain amount of time there, taking part in a process associated with the type of target area. Agents move freely inside the target area for the duration of the task. Depending on the target area and the associated task, a speed reduction factor is applied.

Examples of this are spending time buying a ticket at a ticket counter, performing a certain task at a work station, walking around in a small shop inside a public building or sitting down in a waiting area. Upon completing their task, at a target area the target will assign another target area to the agent.

In our simulation, we assign new targets with a certain probability, which might be derived from analyzing pedestrian data from the modeled building or selected by using expert knowledge. Once assigned a new target, the navigation algorithm calculates a shortest path towards the next target based on the navigation graph and assigns intermediate targets, which are the doors that have to be passed through. For the shortest path calculation, the A* search algorithm is used.

Fig. 4 illustrates the basic navigation approach. The route choice of a pedestrian is determined at the time of target assignment. Thus, changes in the navigation graph during the travel time to this target will not lead to an immediate rerouting. If an agent tries to pass through a door that has been locked, the area will trigger a recalculation of the path towards the target. This recalculation takes into account the new state of the navigation graph and works for an arbitrary position on the plane as the starting position, in order to be able to trigger the rerouting from any position. This is important if we want to portray events like an emergency protocol in a public building where an announcement through speakers to leave the building immediately is made, leading to a rerouting of pedestrians from their current position.

The basic idea of how to use the navigation graph to reroute from an arbitrary position is to add the position as a temporal vertex to the navigation graph with edges connecting it to all doors of the current room. The edge weights are the values of the floor fields of those doors evaluated at the position of the agent. Shortest path calculation is then performed on this temporal graph to determine the new list of intermediate targets. If there is no way to reach the currently assigned target anymore, a new target will be assigned. Target choice naturally depends on the use case for this scenario.

Another possibility of consecutive target assignment for our simulation is giving the agent a full list of consecutive targets, either at generation or at certain targets in the building. This is used if there is a process consisting of different sub-processes in different areas, such as the security scan at an airport, or if the order of processes an agent will take part in is already known before the simulation.

3.4 The Data Model and Interaction Framework

The interaction among simulators is enabled through a shared data source, structured around a comprehensive and extensible data model as proposed by Franke et al. (2023). This model is designed to represent individual components, such as walls, obstacles, pedestrians, pedestrian target areas and others. Each component is characterized by a set of attributes relevant to its function within the simulations. Some attributes, such as a Universally Unique Identifier (UUID) or the position and rotation of the component, are available in all components. In addition, some components define special attributes, such as the velocity and destination of pedestrians, or the length and current flow of power cables. Communication between simulators is implemented using an NGSI-LD (Next Generation Service Interface-Linked Data) information model, managed through a *FIWARE Orion*[2] context broker. This approach ensures standardized and efficient data exchange.

Each simulation running simultaneously subscribes to the components actively involved in its processes. In the case of the pedestrian simulation, the subscribed components include individual pedestrians, pedestrian target areas, doors, and the power fuse. The subscription synchronizes the state of these components between the internal data model of the pedestrian simulation and the shared data source.

Fig. 5 illustrates the software architecture used to couple the pedestrian simulation with a generic simulation of a system that interacts bidirectionally with pedestrian flows.

4 SIMULATION EXAMPLE

In order to demonstrate the capabilities of our model, we examine a scenario in which a saboteur disrupts

[2]FIWARE Orion: https://github.com/telefonicaid/fiware-orion

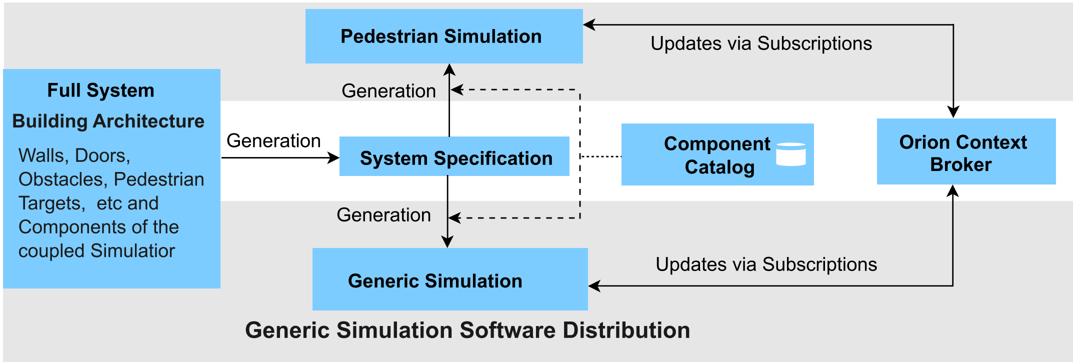


Figure 5: This diagram illustrates the coupling process between the electrical simulation software and the pedestrian stream simulation. The FIWARE Orion Context Broker synchronizes the associated data models.

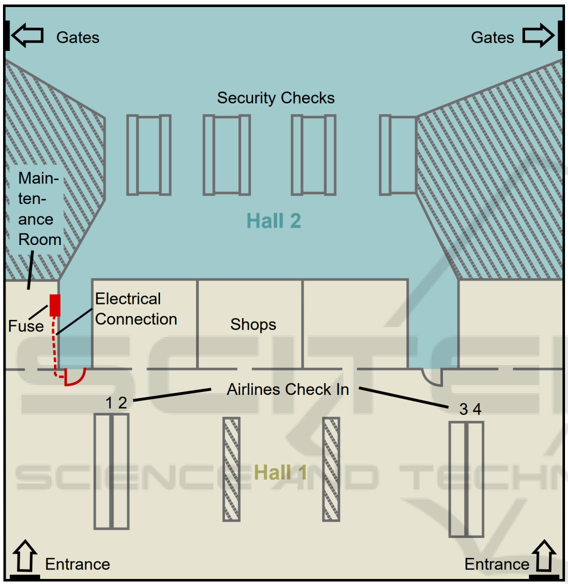


Figure 6: This labeled floor plan illustrates the airport architecture used in our simulation example, marking all relevant stations in the agent's navigation process. The red line represents the electrical circuit which connects the fuse in the maintenance room with the electrical door.

airport operations by removing a fuse. This scenario, previously used as an example in the introduction, serves as a test case for our approach. To simulate this event, we couple our pedestrian simulation with an electrical simulation using the interaction framework described in Section 3.4. The pedestrian simulation captures the movement dynamics of individuals within the airport, while the electrical simulation models the resulting system failure. The electrical simulation is introduced in detail in a dedicated subsection at the end of this section.

Fig. 6 depicts the simplified airport departure terminal architecture that is used as input to the simulation. The architecture consists of two connected halls. Hall 1 includes entrances, check-in counters, several shops, and a maintenance room. Hall 2 contains the security check area and exits leading to the gates. The two halls are linked by two doors, one on the left side and the other on the right side. The electrical motors at the doors leading from Hall 1 to Hall 2 are connected to a fuse box within the target area of the maintenance room. However, the left door and the right door are connected to separate fuses.

Thirty minutes of airport operation are simulated in real-time with one simulation step executed every 0.2 seconds. Pedestrians are generated at the entrances based on a normal distribution that reflects the expected departure times of their flights (parameters are provided in Table 1). Each airline has four associated check-in counters, and passengers select one of them as their target with equal probability. Agents are modeled as circles of radius 25cm (Weidmann, 1993). Upon entering, each pedestrian proceeds to a check-in counter associated with their flight, where they queue for processing. The check-in process is represented by a waiting time at the check-in counter. After completing check-in, they walk to the security check area and queue for one of the available security check lines. The security check process consists of three steps: (1) depositing hand luggage for scanning, (2) undergoing a personal scan, and (3) retrieving their hand luggage. Processing times are assumed to be normally distributed (Schultz, 2010). The parameters for the distributions associated with the target areas are given in Table 2. Once processed, pedestrians move towards the designated exit associated with their flight's gate and are removed from the simulation.

At a randomly determined time during the simulation, drawn from a normal distribution with a mean of 900 seconds and a standard deviation of 300 seconds, an agent of type Saboteur is introduced. This agent proceeds to the maintenance room in Hall 1 and activates the target area connected to the fuse box. The activation of the area represents the removal of

Table 1: Agent creation parameters.

Flight	Agents	Mean	Std. Dev.	Color
Lufthansa	20	300 s	300 s	cyan
Eurowings	20	800 s	300 s	purple
Air Lingus	20	1200 s	300 s	green
Ryanair	20	1500 s	300 s	yellow

Table 2: Waiting times at process steps.

Target Area	Mean Time	Std. Dev.
Check-In Counters	40 s	5 s
Luggage Deposit	25 s	6 s
Security Scan	20 s	5 s
Luggage Withdrawal	30 s	8 s

the fuse. This event triggers the electrical simulation, which recalculates the working_status of all components within the affected power circuit. Here, the switching of the fuse deactivates the motor opening the left door between Hall 1 and Hall 2 (marked in red in Fig. 6). Consequently, the left door becomes unavailable, and remains closed.

The unavailability of the left door prompts the pedestrian simulation to dynamically recalculate the shortest paths for all affected agents. Pedestrians originally planning to use the left door are rerouted to alternative paths, ensuring continuity in the simulation despite the disruption. The simulation is run 20 times to compensate for the influence of random variables.

4.1 Electrical Simulation Model

The electrical simulation model is designed to model the logical behavior of a power circuit, capturing whether components are turned on or off. The model represents the circuit as a tree-like graph, where nodes (components) are connected by edges (electrical connections). Three key statuses define the state of each node in the simulation:

- **Power Status:** Indicates whether a node receives power, which is determined by its parent node's operational status and power supply.
- **Switch Status:** Determines whether an external switch is turned on or off, controlling the flow of power to the node.
- **Working Status:** Reflects whether a node is actively functioning, combining the power status and switch status using logical conjunction.

The simplistic simulation model dynamically recalculates the statuses of all subsequent components in response to changes in switch or main power supply states. This ensures that the system accurately reflects the operational conditions of the power circuit.

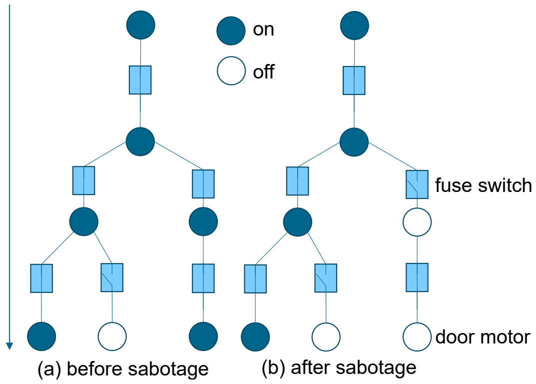


Figure 7: Example of a hierarchically structured electrical circuit as created in the simulation showing the corresponding states before (a) and after (b) the sabotage.

The electric system used in our demonstration setup and the corresponding states before (a) and after (b) the sabotage are shown in Fig. 7. The saboteur entering the target area triggers a fuse on the right tree side, leading to a state change of the right system branch. Thus, the fuse switch cuts the power supply of the door motor, leaving the door out of service.

5 RESULTS

The output of the simulation provides a detailed representation of the agents' states throughout the entire simulation time span, including time (frame), x-coordinate, y-coordinate, viewing direction (angle), absolute velocity V, velocity in x-direction Vx, and velocity in y-direction Vy. A visual representation of this spatio-temporal data is shown in Fig. 8.

The simulation progresses through two distinct phases: before the manipulation of the fuse (Phase 1, Fig. 8a), and after the fuse has been removed (Phase 2, Fig. 8b). During Phase 1, pedestrian movement remains undisturbed, with the left door fully operational. The Saboteur enters the simulation after 754 seconds and walks directly towards the maintenance room. In Phase 2, after the saboteur agent removed the fuse, the electrical simulation updates the power circuit states, marking the left door as non-functional. This update is promptly communicated back to the pedestrian simulation, leading to a re-evaluation of the navigation graph. As a result, all pedestrians adapt their routes to avoid the affected area, as evidenced by the trajectory data presented in Fig. 8b. The number of agents traversing each door is listed in Table 3, further quantifying the impact of the event on pedestrian flow. While during the first phase no agents checking in at the left check-in counters pass through the right door, passenger paths are altered during the second

Table 3: Number of agents traversing each of the doors by time.

Time Interval	Door1	Door2
0s - 983 s	20	6
983 s -1800 s	0	46

Table 4: Duration of upstream and downstream communication.

Interval	Min	Max	Average
upstream	16 ms	24 ms	21 ms
downstream	24 ms	27 ms	25 ms

phase.

To assess the efficiency of the bidirectional communication between the pedestrian and electrical simulations, we measured the time delay between the agent removing the fuse and the pedestrian simulation receiving the updated status of the electrical door.

The total communication delay consists of two components: Upstream, i.e., the time needed to pass the information of the fuse removal from the pedestrian simulation to the electrical simulation, and downstream, i.e., the time between the reception of the information in the electrical simulation and the corresponding update of component attributes of the electrical door in the pedestrian simulation. The corresponding times were tracked using the logs of the context broker. Measurements across the 20 runs are shown in Table 4.

Additionally, the duration of each simulation phase was recorded: Phase 1 lasted an average of 1124 seconds, reflecting the normal distribution of the saboteur's creation time (mean = 900 s) plus the time the saboteur needed to reach the power box (average 227 s), while Phase 2 averaged 676 seconds accordingly.

These results demonstrate the responsiveness of the integrated simulation framework and confirm the successful integration of the pedestrian flow simulation with the electrical simulation, allowing real-time interaction between the two domains.

6 DISCUSSION

In this work, a novel multi-layer navigation model has been proposed. We leverage the advantages of agent-based modeling to portray the complex behavior of individuals, while reducing the necessary computations to achieve a suitable framework for live coupling with other simulators within digital twins of socio-technical systems. The results of our simulation suggest a promising representation of pedestrian behavior and their interaction with technical infrastructure features within a building environment.

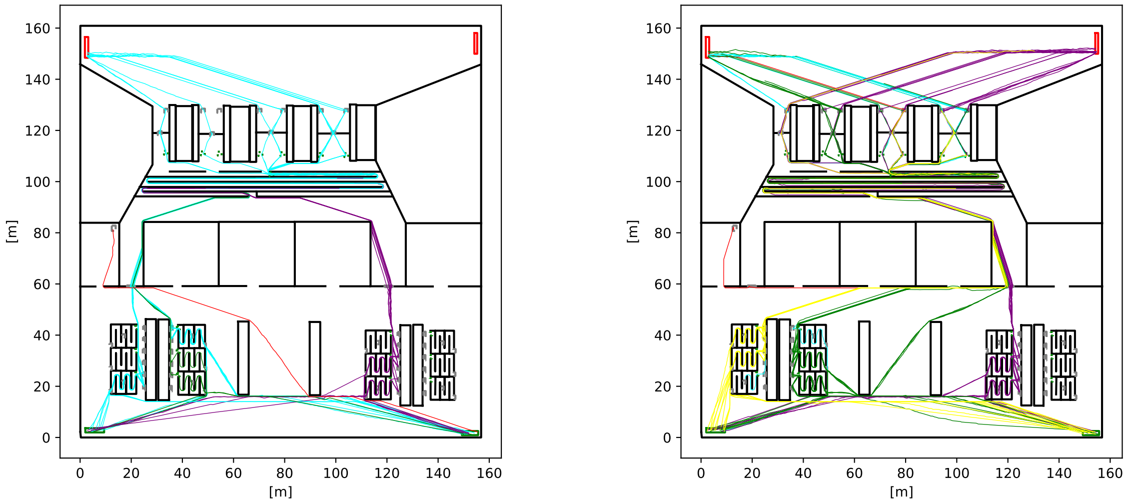
We did not conduct any experimental studies to validate our agents' behavior. However, scientific validation of the underlying model has been performed by von Sivers and Köster (2015). By expanding these validated models to include dynamic environmental updates, we aim to provide a more comprehensive simulation for studying pedestrian dynamics in complex buildings.

Moreover, our model allows direct real-time coupling between different simulation models, as it is not based on a predefined event tree like other state-of-the-art implementations of pedestrian flow simulations, such as Vadere (Kleinmeier et al., 2019).

Additionally, the navigation model employed within the pedestrian simulation proves advantageous for such interactions, enabling efficient and dynamic path recalculations in response to environmental changes. As shown in the output trajectories, our model successfully integrates temporal variations in the environment, such as the locking of a door resulting in the temporary inaccessibility of a pathway.

In our current implementation, agents are rerouted by interacting with the door. However, multiple pedestrians walking toward the same locked door, each trying to open it before choosing a new path toward their target, is not realistic behavior. Instead, the implementation can be improved by allowing one pedestrian to attempt to open the door and triggering the rerouting of all pedestrians steering toward this door who are either in a certain proximity or within the same room. Different methods of modeling the available information about the accessibility of target areas and passages might be applied depending on the use case. How pedestrians share information about which passages are open and other navigation-related details varies greatly depending on the specific use case and is a topic that requires further research.

Another issue with our current implementation is that agents sometimes overstep into a locked door before realizing it is inaccessible, which leads to problems. This issue can be attributed to the fact that the navigation field of a door spans both adjacent rooms. To mitigate this problem in the future, we propose replacing single nodes for doors in the navigation graph with two nodes: one representing each room that the door connects. By doing so, we will introduce two separate navigation fields per door. As a consequence, inaccessibility can be represented by removing the edge between these two nodes rather than the nodes



(a) t = 0 s - 755 s

(b) t = 755 s - 983 s

Figure 8: Agent trajectories for different time windows: (a) Until the saboteur removes the power fuse, (b) After the electrical left door is not operational. The red trajectory shows the path of the saboteur.

themselves, as is currently done. This change should improve the overall reliability and robustness of our system while also reducing the likelihood of agents overstepping into locked doors.

The optimal-steps model does not capture the fact that people will already adjust their pathing to steer around congestions of other pedestrians in sight when they are still far away, unless they estimate that congestion will dissolve before they reach that area. Thus, our model is also subject to this limitation. This could be resolved by incorporating line-of-sight considerations between congestion and the agent, using its orientation in the navigation graph, as shown in previous work (Kneidl et al., 2013).

Furthermore, the shown example assumes prior knowledge of the building geometry for all agents. In reality, however, not all pedestrians possess this knowledge and may rely on their sight and information signs for their routing decisions at a strategic level. Proper use of in-between targets and target assignment within these in-between targets can help address this issue.

Currently, we have not accounted for multiple floor levels within a building. However, stairs and other connection points between floor levels can be integrated to enhance our method. Including the real-time accessibility of elevators connecting different floors into the pedestrian flow model might be an interesting application for the presented approach.

7 CONCLUSION

Pedestrian flow simulation plays a crucial role in realistically depicting the daily activities and dynamics of infrastructure, such as airports and train stations. However, current models are unable to incorporate the influence of external factors by coupling the simulation with other simulators or sensor data.

In this work, we propose a hybrid navigation approach that enhances the optimal steps model with an interactive navigation graph while preserving its advantages. The software architecture we use does not impose limitations on the number of coupled simulations and enables seamless information sharing between them. Consequently, other technical systems, such as water infrastructure, can also be integrated. We have successfully applied our method using a minimal example setup. The integration of pedestrian flow simulation with electrical simulation represents a step forward in creating comprehensive digital twins for buildings, as it expands the scope of scenarios that can be simulated and optimized. Improving the navigation model and its implementation to accurately handle problems like over-stepping, as well as expanding it in order to simulate buildings with multiple floors will be part of future work.

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