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Development of an Unreal®Engine–Based Evacuation Simulation Tool for Passenger Vessels

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1 Abstract

Safely evacuating passengers from large vessels remains a critical challenge in maritime safety. High occupancies, multi-deck layouts and narrow circulation routes become even more difficult to manage under dynamic conditions such as fire, flooding, or vessel motion. This paper presents the development of an evacuation simulation tool built in Unreal® Engine, structured to comply with International Maritime Organization (IMO) guidelines and validated against all twelve benchmark scenarios. The tool integrates graph-based pathfinding, hybrid collision-avoidance methods and IMO-compliant population modelling to simulate realistic passenger flows through corridors, staircases, and muster stations. These results establish a validated baseline for further development.

The focus of this paper is the design and validation of the tool, while advanced features are under development. Future extensions include integration of live sensor data to support dynamic evacuation management by detecting congestion, blocked exits, and hazard spread. Additional work will model vessel heel and trim, refine fire and smoke propagation and incorporate detailed behaviours such as group evacuations or crawling in smoke-filled spaces.

By establishing this foundation, the study demonstrates how Unreal® Engine can deliver high-fidelity evacuation models that meet regulatory standards and provide pathways for decision-support, crew training, and wider applications such as port evacuations.

Keywords: Maritime evacuation, Passenger vessel safety, Real-time simulation, Decision-support system, Unreal®Engine

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2 Introduction

Ensuring the safe evacuation of passengers remains one of the most critical challenges in the maritime sector. Passenger and cruise vessels combine high occupancy levels with complex multi-deck layouts, narrow passageways, and limited vertical circulation. In addition to these structural constraints, evacuations are further complicated by dynamic conditions such as vessel heeling, fire, and flooding, all of which can significantly affect evacuation performance and passenger survivability (Li et al., 2024).

Several maritime disasters highlight evacuation failures: the Costa Concordia grounding in 2012 killed 32 people due to listing and delayed evacuation (Alexander, 2012). In 2014, the Norman Atlantic ferry fire claimed at least 11 lives amid smoke-filled decks and absent alarms (Q. Xie et al., 2020). These tragedies illustrate the urgent need for realistic evacuation modelling and decision support tools.

3 Background

To strengthen passenger ship safety, the International Maritime Organization (IMO) introduced formal guidelines for evacuation analysis (IMO MSC.1/Circ1238, 2003; IMO MSC.1-Circ.1533, 2016). In the past, compliance was often demonstrated with simplified hand calculations, but these quickly proved inadequate for modern, complex vessels. As a result, advanced computational methods have become necessary, with software-based simulators now serving as the standard tool to realistically assess layouts, passenger diversity, and evolving hazards during evacuation (Guarin et al., 2014; Stefanou et al., 2024).

Several evacuation tools have been developed over the years and reviewed by (Stefanou et al., 2024), including EXODUS, IMEX/BY-PASS, AENEAS, VELOS, EVAC, and Evi. These models introduced advances such as pedestrian dynamics, ship-motion effects, virtual reality, and multi-agent simulation. While effective for compliance, they remain largely static and limited in adapting to evolving hazards or real-time conditions.

Building on these limitations, European research initiatives have underlined the need for more innovative approaches. The SAFEGUARD project (Galea et al., 2012) carried out large-scale evacuation trials and proposed extensions to IMO benchmarks. More recently, the H2020 SafePASS project (Boulougouris et al., 2020) focused on developing next-generation evacuation management systems that integrate smart technologies, real-time monitoring, and adaptive guidance to passengers and crew. These initiatives demonstrate both the feasibility and necessity of moving beyond static evacuation analysis toward dynamic, technology-enhanced solutions, reinforcing the motivation for developing tools such as the present Unreal®Engine –based simulator.

Despite regulatory advances and the availability of commercial evacuation software, existing models continue to present several limitations that restrict their ability to fully capture the complexity of real shipboard evacuations (Lee et al., 2003):

- **Static environmental assumptions.**

  Most tools simulate evacuation in a static environment, where ship motion is neglected. Heeling and trim angles, and their associated changes in buoyancy forces, are rarely incorporated. In reality, ship inclination significantly affects passenger balance, walking speeds, and stair traversal (Chen et al., 2025; Tsychkova, 2000).

- **Limited hazard responsiveness.**

  While fire and smoke are sometimes modelled as static obstacles, few systems adjust agent walking speed, visibility, or reaction times dynamically in response to evolving hazard conditions such as smoke density, temperature rise, or toxic gas spread (Kuligowski, 2016).

- **Simplified behavioural assumptions.**

  Passengers are often represented as independent agents with uniform compliance. In practice, grouped behaviour (e.g., families moving together, passengers assisting persons with reduced mobility) introduces delays and local congestion that are seldom captured (Żydek et al., 2021).

- **Rigid routing strategies.**

  Path assignment in several existing tools is based on shortest paths only, with little adaptability to congestion or dynamically blocked exits. This limits their predictive accuracy under realistic emergency conditions.

- **Visualization and user interaction.**

  The outputs of many commercial tools are primarily tabular or schematic, with relatively limited 3D visualization. This reduces their effectiveness for training, communication with stakeholders, and operator preparedness.

It should also be emphasized that static evacuation remains the standard practice in real-world ship operations. Evacuation analyses are generally performed at the design stage and rarely updated once the vessel is in service. This approach overlooks the potential benefits of dynamic evacuation solutions that could incorporate real-time sensor data, evolving hazard conditions and adaptive routing. Investing in such solutions would not only enhance passenger safety but also provide onboard decision-support systems to assist crew and operators in managing emergencies as they unfold.

The tool presented in this study is designed to complement existing software solutions by implementing an Unreal®Engine –based evacuation model that is compliant with IMO benchmarks but also extends functionality through high-fidelity visualisation, modularity, and the potential for dynamic hazard integration. Unlike static compliance tools, the proposed simulator aims to serve as both a research platform and a foundation for real-time, decision-support systems onboard passenger vessels.

4 Methodology

Game engines such as Unreal®Engine have recently been adopted for engineering visualisation and training simulators (Sun et al., 2025). Their ability to combine photorealistic rendering, real-time physics, and customizable AI frameworks presents opportunities to enhance evacuation modelling beyond traditional software (Tugarinov et al., 2020).

The evacuation tool developed is depicted in Figure 1. In the diagram below the high-level development of the tool is depicted in the right-hand side (Figure 1a), while on the left the analytical building blocks of tools are presented with all data flows between processes (Figure 1b). The implementation relies primarily on Unreal®Engine's Blueprint system for flexible prototyping and visual programming, while performance-intensive tasks, such as collision avoidance calculations and other CPU-heavy processes, are executed in C++ to ensure computational efficiency.

Agents plan their routes using A* and Dijkstra's algorithm on Unreal®Engine's navigation mesh (NavMesh). This setup enables each simulated passenger to find a valid path to their designated muster station, taking into account the vessel's layout and available exits (Y. Xie et al., 2022).

Interactions are modelled using Unreal®Engine's Crowd Manager in conjunction with the Reciprocal Velocity Obstacles (RVO) system algorithm, which refines agent trajectories by dynamically adjusting velocities to maintain collision-free motion. This allows individuals to adapt their walking speed and direction in real time to avoid bumping into others, resulting in smoother and more natural-looking flows even under crowded conditions. Unlike cellular automata models, which rely on a grid to control movement, this continuous approach supports fluid motion and more detailed visualisation.

Each agent is assigned characteristics that follow IMO guidelines, including demographic mix, walking speeds, acceleration profiles and awareness delays.

The process begins with geometry modelling, where the vessel's structure—including decks, doors, and stairs—is created in 3d modelling software imported into Unreal®Engine. From this geometry, a navigation mesh (NavMesh) is generated, defining the walkable areas that agents can use. In parallel, population initialisation is carried out according to IMO guidelines, assigning agents with attributes such as age, gender, walking speeds, acceleration ramp-up profiles, and awareness times. Muster stations and fire zones are then specified to define the evacuation objectives.

Using this setup, *pathfinding algorithms (A* and Dijkstra)* compute routes on the NavMesh.

The green path represents the validation cycle also shown in the high-level development. The tool is tested against IMO benchmark scenarios, which specify standardised layouts and conditions. The outcomes—such as total evacuation time and flow rates—are compared with prescribed criteria. Finally, the results and post-processing module aggregates outputs from multiple simulation runs, enabling batch reporting and statistical analysis. These results also act as feedback, guiding refinements in geometry, population settings, or routing parameters, thereby closing the loop between simulation and validation.

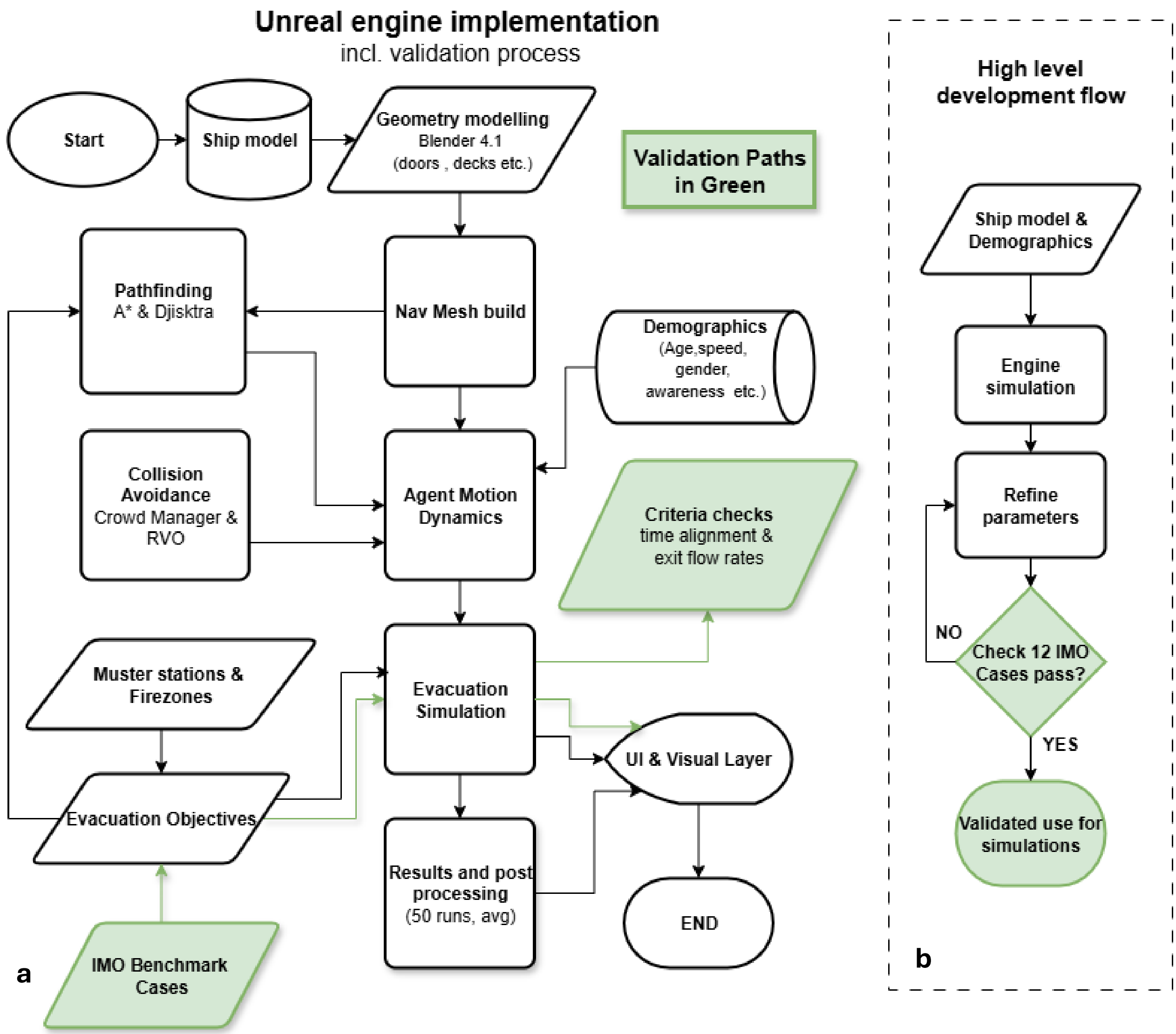

Figure 1a. Architecture of the evacuation tool – Figure 1b. High level development flow

4.1 Geometry, Vessel Layout & Muster Stations' definition

The vessel geometry for the simulation tool is modelled in *Blender 4.1* and subsequently imported into *Unreal®Engine 5*. This ensures high fidelity of the ship's internal arrangement but is also recognised as time-consuming and technically demanding. For future developments, alternative approaches will be explored to streamline the process, including more direct import pipelines and faster geometry preparation.

Special attention is given to the dimensional accuracy of the imported geometry. Deck heights, corridor widths, and door widths are carefully adjusted to ensure consistency with both the actual general arrangement (GA) plans of the passenger vessel simulated and with the constraints defined in IMO guidelines. This alignment guarantees that the simulation reflects realistic evacuation conditions and remains compliant with international regulatory requirements.

Particular effort is dedicated to the accurate representation of staircases, as they are critical bottlenecks in shipboard evacuations. The stair imports are refined to eliminate irregular or dented surfaces that could lead to agents becoming trapped, thereby ensuring smooth transitions between decks and preserving realistic passenger flows.

Finally, muster stations are defined as the designated safe areas to which passengers are directed during evacuation. However, unlike conventional evacuation software the present tool introduces the concept of muster points within each muster station. These points subdivide the larger safe areas into smaller, well-defined zones. By doing so, the tool avoids excessive clustering at station entrances, prevents agents from forming dense blocks that hinder circulation, and reduces the likelihood of congestion that could otherwise prolong the overall evacuation time. This refinement enables a more precise and realistic simulation of crowd distribution within muster stations reflecting also the impact of the crew members' assistance and orders within the area.

4.2 Population Modelling

The population model implemented in the evacuation tool aligns with the demographic composition and behavioural attributes prescribed by the International Maritime Organization (IMO) guidelines (IMO MSC.1-Circ.1533, 2016). The distribution of male and female passengers across different age groups follows the standard IMO age profiles, ensuring alignment with benchmark requirements for both daytime and night-time scenarios.

Each agent is assigned a set of movement-related attributes based on IMO reference values. These include walking speeds on flat terrain, adjusted speeds for ascending or descending stairs and awareness times representing the delay between alarm initiation and evacuation response. Each agent has a fixed radius of 0.2 m and to prevent crossing boundaries, an additional 0.2 m virtual buffer is applied, meaning agents require at least 0.4 m of clearance from walls or obstacles. This combined distance ensures sufficient personal space for movement and avoids invalid spaces that are too small to accommodate agents (Safety At Sea, 2017). Finally, passengers are assumed to follow nearest exit signage when seeking evacuation routes, unless specific instructions are predefined.

4.3 Motion and Collision Avoidance

In evacuation modelling, pathfinding alone is not sufficient to produce realistic pedestrian motion, since it only accounts for static obstacles. To handle close-range interactions between moving agents, the present tool combines both the Reciprocal Velocity Obstacles (RVO) system algorithm and the Detour Crowd Manager (EPICGAMES, 2025) to implement a collision avoidance system.

The RVO method is a velocity-based steering algorithm that computes a set of feasible velocity vectors for each agent at every simulation step. It assumes that nearby agents will continue moving at constant velocity within a short time horizon, and it selects the new velocity that is both collision-free and as close as possible to the agent's preferred direction of travel. Unreal®Engine's implementation of RVO includes optimizations such as frame-rate independence, a collision priority system, and mechanisms to reduce unnecessary path recalculations. RVO is integrated into the Character Movement component, which allowed us to assign demographic-specific movement properties (e.g., speed distributions, acceleration ramp-up times) and tune final values in Editor.

The Detour Crowd Manager, by contrast, extends RVO with an adaptive velocity sampling method that biases sampling toward the target direction, improving avoidance quality in congested environments. It additionally considers visibility and topological corridor information, which makes avoidance more consistent with the global navigation mesh. The Crowd Manager is highly configurable, allowing specification of sampling patterns, agent radius, and maximum agent numbers.

This combination exploits the strengths of both: the computational efficiency, direct character-level integration of RVO and crowd-level coordination of the Detour Crowd Manager. By running both systems in parallel, the simulation benefits from smooth, collision-free trajectories at the local level while maintaining robustness in dense, multi-agent scenarios such as those prescribed by IMO benchmarks.

4.4 Software Validation

Validation of the developed evacuation tool is performed using the twelve benchmark scenarios defined in the IMO Guidelines for Evacuation Analysis for passenger ship evacuation analysis. These scenarios are widely used as a regulatory reference for verifying the compliance of evacuation models and assessing their ability to capture critical evacuation phenomena under simplified but representative conditions. Successful reproduction of these scenarios is considered a prerequisite for any evacuation simulation software intended for use in maritime safety studies.

All twelve scenarios are implemented within the Unreal®Engine –based tool, incorporating simplified geometries, population distributions, and exit arrangements as prescribed by IMO guidelines (IMO MSC.1-Circ.1533, 2016). The scenarios are simulated with multiple runs to account for stochastic variations in population behaviour. In each case, evacuation times, exit flow rates, and clearance profiles have been compared against the IMO acceptance criteria.

A brief summary of the benchmark cases is as follows:

- Test 1: Maintaining set walking speed in corridor
- Test 2: Maintaining set walking speed up staircase
- Test 3: Maintaining set walking speed down staircase
- Test 4: Exit flow rate
- Test 5: Response duration

- Test 6: Rounding corners
- Test 7: Assignment of population demographics parameters
- Test 8: Counterflow – two rooms connected via a corridor
- Test 9: Exit flow: crowd dissipation from a large public room
- Test 10: Exit route allocation
- Test 11: Staircase
- Test 12: Flow density relation

The tool successfully reproduces the expected results across all cases, demonstrating regulatory compliance. This provides a robust validation baseline and ensures comparability with existing commercial evacuation software, while leveraging Unreal®Engine's enhanced visualisation and extensibility.

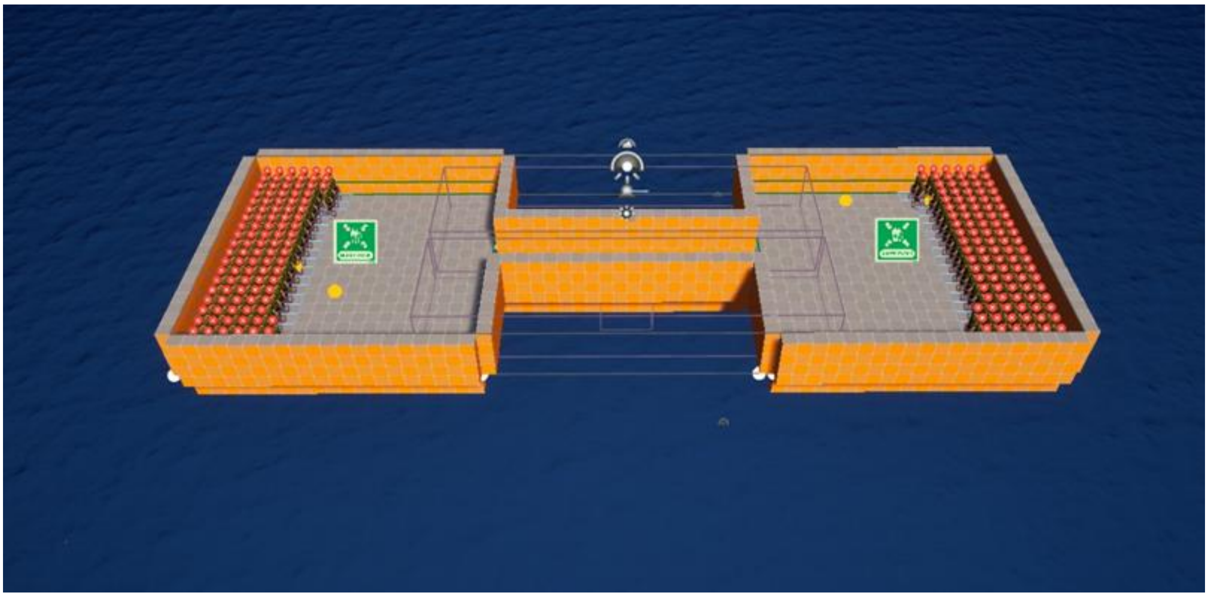

Figure 2. Validation process - Testing 8_4 benchmarking case

In addition to performing the IMO benchmark scenarios once for validation, all twelve test cases have been embedded directly into the evacuation tool as predefined modules. This integration allows users to re-run the tests at any time, ensuring continued compliance with regulatory standards as the tool evolves. It also provides a convenient way to demonstrate validation results to stakeholders, since benchmark outputs—such as evacuation times, density profiles, and flow rates—can be reproduced and displayed on demand. Embedding the scenarios in the software therefore enhances transparency, facilitates verification, and strengthens confidence in the reliability of the tool.

5 Expected results

The software, after successful compliance with the IMO standards, has been designed to extend beyond static evaluations and support dynamic evacuation management.

The key anticipated results include:

- ✓ **Integration of hazard modelling.** The platform supports hazard modules for fire, smoke, flooding, and vessel motion, with planned extensions to model heel and trim via buoyancy forces or passenger crawling under smoke. In this way, evacuation can be analysed under evolving conditions rather than predefined static obstacles.

- ✓ **Predictive routing algorithms.** Routing will adapt dynamically to hazards or congestion, allowing agents to re-calculate evacuation paths when conditions change.
- ✓ **Input sources.** The tool is structured to rely on live and simulated data streams, including fire/smoke detectors, occupancy tracking, and flooding sensors.
- ✓ **Output interfaces.** Evacuation instructions are expected to be exportable to signage, mobile applications, and smart wearables such as lifejackets with haptic feedback or chatbot-based assistance. This approach has been inspired by the SafePASS project outcomes (Stefanidis et al., 2023).

In Figure 3, the simulation environment is illustrated with agents shown in different stages of mustering. Green markers indicate agents who have successfully reached the designated muster areas, while red markers represent those still in transit. At the lower part of the figure, an example of fire propagation during evacuation is visualised, demonstrating how hazards are incorporated into the simulation. At the centre, the user interface (UI) is displayed, providing critical information such as the number of agents mustered over time, simulation speed and other key performance indicators.

Figure 3. UI and 3d representation of the vessel conducting evacuation simulations

5.1 Simulation Results and Reporting

The evacuation tool is designed to produce results that are both quantitatively robust and visually interpretable, ensuring alignment with IMO requirements while offering added value for research and operational use.

At present, simulations run in real time—for example, a one-hour evacuation requires roughly one hour to compute. Using a Ryzen 9 7900 CPU with an RX 7800XT GPU and 32 GB RAM, performance averaged around 100 FPS for simple layouts with under 1,000 agents, and 2.7–3.2 FPS for complex cruise-ship geometries with about 5,000 agents. Future work will focus on reducing runtime through code-level optimisation, including refining execution timing, minimising costly function calls, and streamlining cast operations, supported by more powerful hardware where necessary.

A wide range of performance metrics will be available to evaluate evacuation effectiveness, including:

- **Total evacuation time**, defined as the duration until all agents reach their designated muster stations.
- **Per-deck clearance times**, allowing assessment of localized evacuation efficiency and identification of bottlenecks.
- **Door and staircase utilisation rates**, indicating how architectural features and flow capacities influence evacuation dynamics.
- **Density maps and temporal congestion profiles**, which highlight crowd build-up in specific areas and quantify how it evolves over time.

To avoid relying on a single stochastic outcome, the tool will be able to simulate multiple runs of each scenario (batch running). Results are then summarised using averages, ranges and the 95th percentile, giving a more reliable and representative picture of evacuation performance.

Another key feature is the ability to replay simulations in 3D, either in real time or slow motion. This not only helps with technical validation but also makes it easier to explain results or spot bottlenecks by showing how agents move through the ship under different conditions.

Finally, Unreal®Engine provides a flexible communication layer, enabling evacuation instructions to be displayed through operator dashboards, dynamic signage, mobile applications, or smart wearables. This feature aligns with the vision of using the tool as a decision-support system during real emergencies, while also serving as a training platform for crew and as a research testbed for new evacuation strategies.

6 Discussion

The Unreal®Engine –based evacuation tool presented successfully reproduces all IMO benchmark scenarios, ensuring compliance with international standards. Beyond validation, the tool shows how game engines can enhance evacuation analysis, moving away from static, design-stage evaluations toward dynamic and immersive simulations.

A central focus of the tool is its potential for real-time evacuation management. It is intended to rely on live sensor data, enabling the detection of congested routes, blocked exits or spreading hazards and the dynamic adaptation of passenger routing. This capability would allow evacuations to be represented and managed under evolving onboard conditions, directly supporting the transition from compliance-focused simulations to operational decision-support applications.

Several development challenges remain, but the tool is already designed to address them, and work is underway to extend its capabilities. High-fidelity rendering and physics can increase computational demand for large passenger populations, yet optimization strategies are being integrated to ensure scalability. While demographics are currently modelled in line with IMO guidelines, social-group behaviours such as families evacuating together or passengers assisting others are being implemented. Hazard modules for fire, smoke, and flooding are simplified in the present version, but extensions are in progress to incorporate more detailed propagation models. Likewise, the tool is prepared to simulate heel and trim through buoyancy forces, adjusting walking speeds according to vessel inclination and position. Finally, scenarios in which passengers may be forced to crawl due to dense smoke and reduced visibility are under development, with corresponding speed adjustments to improve behavioural fidelity. Beyond passenger vessels, the tool also shows promise for port evacuations and other safety-critical infrastructures, where large crowds must be dynamically managed under stress. Overall, the presented tool offers a foundation for next-generation evacuation simulation.

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