Passenger Ship Evacuation – Design and Verification

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Abstract. This paper introduces the concept of escape and evacuation from passenger ships from a perspective of ship design and risk management. As part of that process, the use of computer simulation tools for analysing the evacuation performance of ships carrying large numbers of persons on board is becoming more relevant and useful. The objective of this paper is to present the pedestrian dynamics simulation tool EVI, developed to undertake advanced escape and evacuation analysis in the design verification of cruise vessels, passenger ferries and large offshore construction vessels, among others.

Keywords: Evacuation analysis, passenger ships, offshore vessels.

1 Introduction

Innovation in ship design has traditionally been a feature of the cruise and ferry sectors of the maritime industry. The design of passenger ships has evolved dramatically during the past 30 years, driven among others, by increasing customer expectations, business opportunities, technological progress and societal demands for increased safety and environmental greenness. The single most significant trend is the growth in ship size, with the largest cruise vessel today being able to carry more than 5000 passengers on-board (some 8,400 people including the crew), and measuring more than 350m in length.

Another trend in the industry has been fuelled by the emergence of offshore construction, which has led to the development of a new type of working vessels with the capacity to carry and accommodate large number of special personnel (workers) on board. These vessels, referred to as Special Purpose Ships (SPS), may be subject to the same rigorous design verification as large passenger ships when the numbers of persons on board exceed 240.

Safety is arguably the single most significant design driver for passenger ships today with safety requirements now driven by explicit safety goals and include quantitative verification of residual capabilities in case of accidental events. Those capabilities relate to stability after flooding extensive fire protection, redundancy of essential ship systems (in line with the 'safe return to port' philosophy) and ultimately escape and evacuation arrangements – the last safety barrier if everything else fails.

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Given this level of significance, validation of escape and evacuation arrangements is gradually taking a more prominent place in the conceptual ship design iteration and verification process. To this end, following initial developments at the University of Strathclyde in the late-1990s to support the rule-making process, the focus at Safety at Sea since 2001 has been clearly on ship design/operation support. Initially, the software was designed to undertake advanced evacuation analysis for Ro-Ro passenger vessels in accordance with the guidelines developed by the International Maritime Organization [1]. More recently, the software has been used as a consequence analysis tool during the conceptual design risk analysis of large passenger vessels, offshore platforms and special purpose ships (pipe layers, drilling ships, crane vessels, among others).

A brief overview of the ship-evacuation problem is presented in Section 2 with emphasis on the many factors that influence the process of ship evacuation. In Section 3, a general description of the key features of the EVI simulation model is presented. These key features represent the concept and implementation of the solution to the problem defined in Section 2.

The paper concludes in Section 4 with some practical observations based on the experience gained from the use of the tool in a number of commercial applications and design projects.

2 Ship-Based Evacuation Problem

The ship evacuation process has a number of aspects which influence the outcome of a ship evacuation and therefore have to be taken into account when trying to simulate and analyse the process. A brief overview of these factors is given in the following.

2.1 Emergency Scenarios

A ship may need to be evacuated in an emergency if the risk to the persons on-board is deemed to be unacceptable. For the majority of ships, emergency scenarios requiring ship abandonment may be associated with shipping accidents, such as collision/grounding leading to flooding, fire or explosions. A generic procedure, referred to as ‘muster list’, for dealing with an incident is illustrated in **Table 1**. As it can be noted, the process of evacuation is normally carried out in stages. In each stage, there might be different activities occurring concurrently but having different objectives.

Table 1. Generic (typical) muster list for a passenger ship

STAGE 1	STAGE 2	STAGE 3
INCIDENT (1) Detection & Alarm	(2) Damage control (3) Muster of Pax (4) Preparation of LSA	(5) Abandon Ship (6) Rescue

The incident itself (e.g. fire, flooding) might physically impact on the evacuation arrangements. This impact can include the following:

- Impairment/inaccessibility of escape routes, muster areas or evacuation systems (e.g. due to damage, heat, smoke or floodwater);
- Heel and/or trim of the ship (due to flooding), leading to inclination of the surfaces used as escape routes; these may slow down the movement of evacuees or stop them altogether. Severe inclinations (more than 20 degrees) can prevent the occupants from deploying evacuation systems.

2.2 The Ship Environment

The ship purpose determines the internal layout of the ship. The layout is a complex collection of spaces of different use, distributed along horizontal decks and vertical fire zones. The function of the spaces varies greatly from ship to ship:

- **Passenger Vessels:** Layout includes a variety of public spaces (such as restaurants, theatres, shopping malls, lobbies, sun decks, bars, discos, casinos and many others), cabins and crew service spaces (machinery, galleys, hotel services, etc.)
- **Offshore Vessels:** Layout includes a variety of spaces in the living quarters (cabins, recreation spaces, meeting rooms, offices, control rooms, etc.), working stations for special personnel (pipe manufacturing stations, crane workstations, working decks, etc.) and marine crew service spaces (machinery, workshops, stores, etc.).

The geometrical and topological features as well as the different functions of spaces within a ship will greatly influence the location of the evacuees at the moment of the incident and in some cases, the awareness and/or the response time of the occupants. For example, people in cabins may be asleep, people in working stations (e.g. welding, heavy lift cranes) may be subject to a delay due to safe termination of work requirements.

2.3 Escape and Evacuation Arrangements

Escape and evacuation arrangements can be considered as risk control measures or barriers aimed at mitigating the severity of the consequences of an accidental event. These measures are mainly of passive nature and include the following:

Alarm Systems. Public address and alarm systems are the means of communicating an emergency signal to all persons on-board. This will influence the time for people to become aware of and respond to the incident. The General Alarm signalling the order to muster is typically activated by the crew once the incident is validated;

Escape Routes. These comprise hatches, doors, corridors, stairs, walkways, ladders and other spaces, connecting all spaces on-board to a muster area or a safe refuge. Most spaces on-board ships are fitted with at least two emergency exits. All exits lead to a primary and a secondary escape route to a muster point. The capacity of the escape routes is generally driven by the width of the escapes and the redundancy of the routes from different areas of the layout.

Muster Areas. These are spaces that can be located internally (public areas) or externally (near embarkation stations). The capacity and specification of muster areas varies significantly from passenger ships to offshore units/vessels. For passenger ships, at least 0.35 m^2 per person has to be provided (e.g. 500 persons, a minimum of 175 m^2 of deck space has to be provided in the muster area).

Lifesaving Systems. These comprise survival craft (e.g. lifeboats) and other systems to assist in the abandonment of the ship. These systems have to be prepared before use (if not stowed in the embarkation position) and are usually located near or by the muster areas. The capacities of these systems vary from ship to ship. Typically, lifeboats for up to 150 persons are fitted to most passenger ships. Recently lifeboats with capacities up to 370 persons have been developed. The arrangement of survival craft can significantly influence the procedures and time of ship abandonment.

2.4 Human and Organisational Factors

Number of Persons on Board (POB). The number of POB depends on the purpose of the vessel/offshore unit and the operational mode. A typical cruise vessel carries about 4000 persons (including crew). Offshore construction vessels may carry up to 600 persons.

Demographics. The demographic characteristics (age, gender, etc.) of the evacuees would greatly influence the walking speed and the reaction time to an alarm. The demographics differ greatly between passenger ships and offshore working vessels. Whilst on passenger vessels the sample of people is representative of the normal population demographics (including children and people with mobility impairments), on offshore working vessels, the population sample corresponds to personnel specifically trained to work in offshore conditions (the level of fitness, familiarity with the layout, emergency preparedness and competence is significantly higher than that of the typical passengers population).

Crew Emergency Tasks. As indicated in **Table 1**, in most situations, crew are expected to undertake active damage control and assist passengers during the muster and ship abandonment process. Crew emergency tasks involve directing passengers to the correct muster point or to alternative routes if the primary escapes are impaired and reduce the awareness time (active search of people in cabins), among others. This requires active internal communication among crew and between crew and passengers, which in essence amounts to giving and updating the objectives of individual evacuees.

2.5 External Factors

Sea State. The direct impact of wind and waves is on the ship behaviour, which in turn, translates into ship motions. Ship motions-induced accelerations may affect the walking speed of evacuees and even their decision making.

Time of Day. In passenger vessels, the time of day determines the initial location of persons on-board at the moment of an incident. During the night, persons are more likely to be located in cabins and asleep, which decreases their awareness and increases reaction time. During the day, the range of activities on-board and the location of the spaces will determine the choice of muster areas (usually the nearest possible) are the routes they would eventually take to reach the muster points (usually the most familiar). In working ships, the impact of the time of day is lower as these ships usually work in shifts i.e. they have the same persons load during the day and at night.

3 Evacuation Simulation

The software EVI, in its current form, was conceived in 2001 [2]. The first concept of the simulation tool was first presented in 2001 [3]. Since then, the code has undergone further development driven mainly by commercial applications. The key design principles and assumptions are outlined below.

3.1 Multi-agent Simulation

The EVI simulation is an implementation of multi-agent modelling, which is a further generalisation of process-based modelling methods where the environment is very well defined and the agents may communicate in a fairly versatile manner. In natural systems, all component parts "live" in some sort of topological space (predators and prey may live on a two dimensional forest floor, data packages traverse a network graph and the evacuees move around on a 2D deck). An environment is defined to be an artificial representation of this space. Autonomous agents can perform the activities defined by a computer program in this environment. This strong sense of environment does not exist in a process-based simulation. Processes are only aware of themselves and the resources they wish to acquire. Communication in multi-agent simulation describes all interaction between real life entities. This makes multi-agent simulation an extremely powerful tool but also one, which is hard to verify in the context of known mathematical theory. The essence of using agents requires a rigorous definition and full implementation of the environment and its interfaces with the agents as well as an inter-agent communication protocol.

3.2 The Environment

Definition of the environment is one of the most important aspects of multi-agent modelling. This consists of three aspects: (i) geometry, (ii) topology and (iii) domain semantics. The whole ship layout is segmented into Euclidean convex *regions* with a structure of a linear space, directly connected if they have a common gate. This connectivity topology, for all computation and analysis purposes can be represented by a graph.

In ship layout terms, regions correspond to spaces and gates correspond to doors. Regions can be defined as rectangular or convex polygons with attributes that control initial conditions and semantic information that agents may query when traversing through (such as initial number of persons, fire zone, destination, etc.). Regions can be located at different level entities, called decks, defined by the height above a reference level or baseline. The problem of finding the path of an agent to a muster point becomes reduced to searching the topology graph.

3.3 The Agents

The lowest common denominator of the many definitions of "agent" is an encapsulation of code and data, which has its own thread of control and is capable of executing independently the appropriate piece of code depending on its own state (the encapsulated data), the observables (the environment) and the stimuli (messages from other parts of the system or interactively provided). The agent-action model is essentially a 'sense-decide-act' loop. The sense and decide steps may be coalesced, as the sensing is nothing more than the interface of the agent with the data structures representing the environment. The decision process requires access to the perceived information, thus perception is not a complex process but rather a simple access interface between the environment and the agents. Notably, the actions of agents may also change the environment, giving rise to what is called interactive fiction. To address the modelling of human behaviour at the microscopic and macroscopic level, the agent model itself can be seen as being composed of a number of levels, see **Fig. 1**.

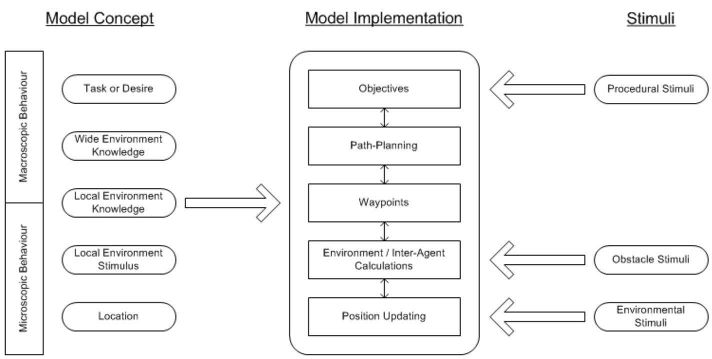

Fig. 1. The agent model in EVI

At the highest level, an Objective defines agent task or desire, for example, go to a cabin and wait for 60 seconds, search all the cabins on deck 7, fire zone 3, port side or evacuate to the nearest assembly station. In order to fulfil this desire, the Objective requests a path plan (routing) to be calculated, which defines what door and the order of the doors the agent should go through to advance from the current location to the destination. Once this data structure is in place, the agent will select a waypoint, an intermediate location to travel to, usually in direct line-of-sight from the agent (i.e. within a convex region), from the first door in the path plan route. With a defined direction to travel to, defined by the waypoint, the agent will move towards that location using position updating. In doing so, the agent will avoid the boundaries of spaces and other agents in the locality by taking account of environment and inter-agent conflicts.

3.4 Mesoscopic Modelling

Ship arrangements are large with many routes from one location to another and endless choices along the way. As a person traverses a route he/she will have to interact with other people along the route and react to the surrounding environment. This gives rise to a need to have two main methods of considering the problem: (i) Macroscopic modelling: addressing the problem of how passengers may find their way from one part of the ship environment to another (high-level planning), and (ii) Microscopic modelling: considering how individuals interact with the environment within close proximity (low-level planning).

Microscopic Behaviour. The microscopic model covers the behaviour of movement of agents within spaces. It dictates the way agents avoid boundaries of spaces and how it should avoid other agents. Given these constraints, the objective is to steer the agent towards a local destination (waypoint) in an optimal manner without being uncooperative towards the other agents in the space.

Environment discretisation and the agents. Given that the environment is discretised into convex *regions*, the process of moving from one door (gate) to another becomes a process of pursuit of a static target. However, with additional complexities such as other agents and obstacles, the process of steering becomes significantly more complex. The decision of how to approach this specific problem is one that determines the entire design of the simulation architecture. In this respect, two general approaches can be identified: (i) grid-based techniques and (ii) social forces models. Both approaches have their merits and constrains. However, EVI combines the effectiveness of grid-based technique with the flexibility of social force methods, see **Fig 2**.

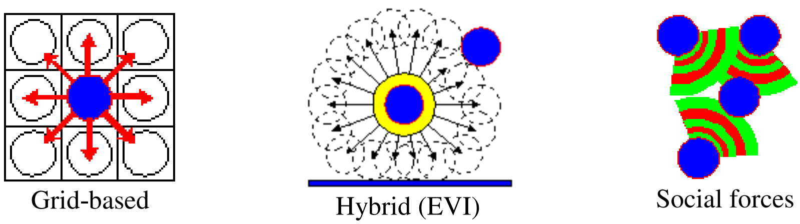

Fig. 2. Agents in the environment

In order to simplify calculation, a range of discrete decisions are established around the agent with the objective of identifying the one which will allow the agent to travel the greatest distance toward the local target. In addition, a continuous local (social/personal) space is established around each agent, which other agents will aim to avoid. This space is used to prevent a deadlock situation when the number of agents in an area becomes high. The agent makes a decision of the best use of its personal space to resolve any conflicts that may arise. As a result, this approach allows the evacuation process to be modelled in sufficient detail and still run in real time or faster. In order to move, each agent needs to be aware of the local surrounding environment and draw conclusions on how to move. This update procedure is defined in terms of three steps: perception, decision and action.

Perception. Agents use their update vector to check their personal space for boundaries (containment) and other agents (collision avoidance and lane formation). This takes place in the form of discrete directions. The magnitude of the vector corresponds to the distance that can be travelled over the time step for a given nominal walking speed.

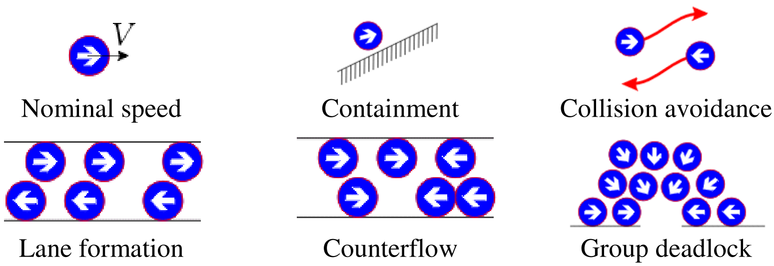

Fig. 3. Agent microscopic behaviour

Decision. A rational rule-based process is used to select the action to take for the current time step. The decision process makes use of information on the previous time step combined with information acquired from the Perception algorithm. The algorithm also gathers state information from the current environment and considers a number of discrete possibilities for updating the agent status:

- Update: The agent should update as normal moving as far along the update vector as possible.
- Wait: The agent does not move.
- Swap with Agent: The agent in collaboration with another on-coming agent has decided to swap positions to resolve deadlock.
- Squeeze through: The agent is congested but perception has indicated that if the agent disregards its personal space it can progress
- Step back: An agent who is squeezing through has violated the personal space of another agent. The direction of update is reversed to allow the squeezing agent through.

Action. This consists of careful updating of the status of all agents based on updating the decisions made. Due to the nature of software programming, this is, of necessity, a sequential activity to avoid loss of synchronisation. To ensure that agents update properly, order is introduced into the system whereby each agent requests those in front, travelling in the same direction, to update first before updating itself.

Macroscopic Behaviour. The macroscopic behaviour defines the way an agent will travel from one location to another on board the ship layout. Building on the graph structure defined within the model, the process of identifying the shortest route to a destination is achieved using Dijkstra's classic shortest path algorithm with the weighting taken as the distance between doors. This concept is very similar to the Potential methods used in other evacuation simulation models except that distance is only considered along the links of the graph rather than throughout space. Once route information has been generated for each node, the process of travelling from one point in the environment to another is just a case of following the sequence of information laid down by the search; this is referred to as the path plan.

Path-plan information is generated on demand when required by agents, and except for cases where the path plan refers to an assembly station, route information is deleted when no longer required. To ensure that the path-planner will respect the signage within the ship arrangement regions and doors attributes include definitions of primary exits and primary routes, which can force agents to use specific routes.

3.5 Modelling Uncertainty

The psychological and physiological attributes of humans are non-deterministic quantities. Even in a contrived experiment one can hardly reproduce human actions/reactions even if all of the conditions remained the same. This inherent unpredictability of human behaviour, especially under unusual and stressful circumstances, requires that human behaviour be modelled with some built-in uncertainty.

Demographics. All parameters related to human decision or action, are modelled as random variables with user-defined probability distributions. This information, referred to as demographics includes variables such as awareness/response time, gender and walking speed, among others, is almost exclusively collected through observational research using experiments that measure the response of people in controlled and uncontrolled environments. Typical demographic information is available from full scale trials in the form of basic statistics; see for example [1] and [5]. This information in conjunction with the probabilistic assumptions is used to carry out Monte-Carlo sampling to derive the values of response time and walking speed for each agent taking part in the simulation.

EVacuability Index (EVI). For the purpose of undertaking evacuation analysis, a number of performance measures can be evaluated, such as time for a group of persons to clear a particular area (ESCAPE), time for all agents to complete assembly after a signal (MUSTER), time for a group or agents to complete escape, muster and ship abandon if these were carried out in sequence (EVACUATION). The choice of performance measure will depend on the specific scenario being evaluated.

Considering the above, the term Evacuability is defined as the probability of the given objective (Escape, Muster, Evacuation, etc.) being achieved within a time t from the moment the corresponding signal is given, for a given state of the ship environment (env) and for a given state of initial distribution (dist) of people in the environment. Thus, results from a number of simulation runs (given that the environment and the distribution remain the same) as a multi-set {t1, t2, t3, t4,… , tn} then by the law of large numbers Evacuability may be determined with an accuracy directly dependent on the number of runs. For practical applications, at least 50 individual simulations of the same evacuation scenario are required, and from these results, the 95 percentile values are used for verification in accordance with IMO guidelines [1].

3.6 Scenario Modelling

Based on the general aspects presented in Section 2, escape and evacuation scenarios may range from local escape from an individual zone of the ship (e.g. due to fire) to a complete ship evacuation (muster and abandon, e.g. due to a flooding incident).
The impact of hazards associated with flooding and fire can be incorporated in EVI in time and space. The software is capable of reading time histories of ship motions and flood water in the ship compartmentation from time-domain flooding simulation tools such as PROTEUS-3.1 [7]. The impact of ship motions and floodwater on the agents is modelled by applying walking speed reduction coefficients that are functions of the inclination of the escape routes due to heel and/or trim of the ship, generated by the damage [5] [6]. The impact on the environment is modelled by way of treating regions directly affected by floodwater as inaccessible.

In terms of fire hazards, the software is capable of importing fire hazards information from fire analysis tools such as FDS [8]. Fire hazards are described in the form of parameters such as temperature, heat fluxes, concentrations of toxic gases (such as CO, CO_2) and oxygen, smoke density, visibility, etc. The impact of these hazards on the agents is modelled by comparing against human tolerability criteria [6].

4 Conclusions

This paper presents a high level description of the concept and implementation of the multi-agent simulation tool EVI – a pedestrian dynamics simulation environment developed with the aim of undertaking escape and evacuation analysis of passenger vessels in accordance with IMO guidelines [1].

Multi-agent simulations are computationally intensive; however for practical engineering applications, they have become viable with the advent of cheap and high computing power.
The particular implementation of EVI combines a number of concepts and approaches which make EVI a versatile tool suitable for efficient and practical design verification.

Due to the implicit level of uncertainty in the process, driven by human behaviour, verification of the tool has been successfully achieved in terms of component testing, functional and qualitative verification [4][5]. Data for quantitative verification is still lacking.

Over the past 5 years, EVI has evolved into a consequence analysis tool for design verification of passenger ships and SPS (offshore construction vessels, pipe-laying, large crane vessels) subject to design risk analysis. Among this type of applications, the following can be highlighted:

- Verification of escape arrangements for alternative design & arrangements: this is part of the engineering analysis required in accordance with IMO MSC\Circ.1002, see **Fig. 4**;
- Escape, evacuation and rescue assessment for SPS (offshore construction vessels carrying more than 240 personnel onboard) – see **Fig. 5**.
- Analysis of turnaround time in passenger ship terminals – see **Fig. 6**.

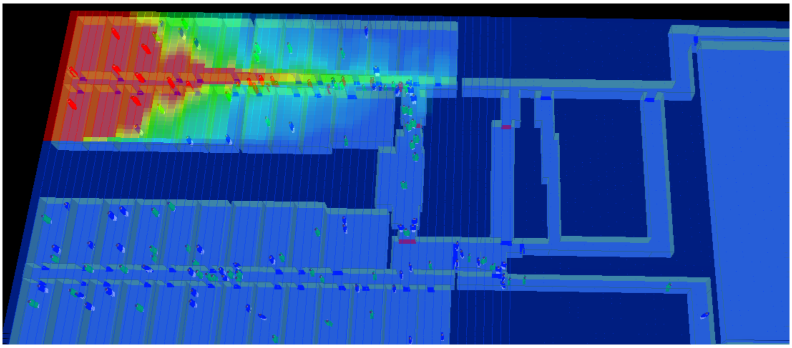

Fig. 4. Verification of human tenability criteria for a layout fire zone

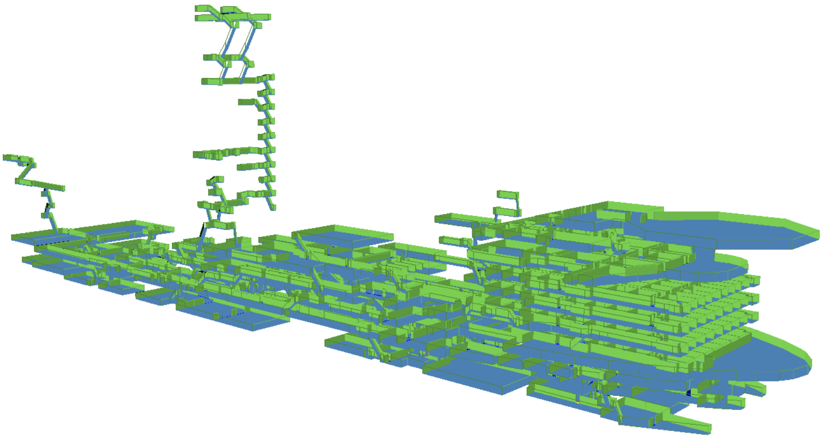

Fig. 5. EVI model of a pipe-laying vessel (LQs with accommodation for 350 POB) for evacuation analysis

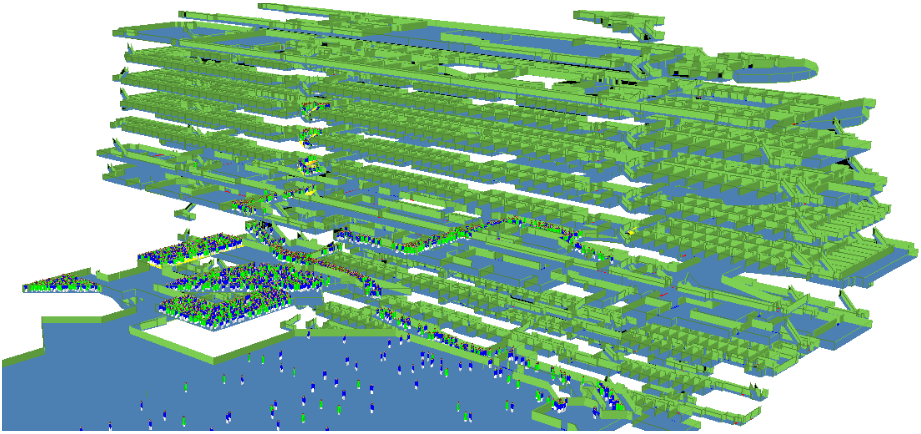

Fig. 6. EVI model of a Ro-Ro passenger ferry at the terminal for turnaround time analysis (2700 passengers disembarking)

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