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VELOS: A VR platform for ship-evacuation analysis

A.I. Ginnis [a], K.V. Kostas [a], C.G. Politis [b], P.D. Kaklis [a,*]

[a] *National Technical University of Athens (NTUA), School of Naval Architecture & Marine Engineering, CAGD/CAD/VR Group, Ship Design Laboratory, 9 Heroon Polytechneiou, GR-157 73, Zografou, Greece*

[b] *Technological Educational Institute of Athens, School of Technological Applications, Department of Naval Architecture, Agiou Spyridonos & Dimitsanas, GR-122 10, Aigaleo, Greece*

ABSTRACT

"Virtual Environment for Life On Ships" (VELOS) is a multi-user Virtual Reality (VR) system that aims to support designers to assess (early in the design process) passenger and crew activities on a ship for both normal and hectic conditions of operations and to improve ship design accordingly. This article focuses on presenting the novel features of VELOS related to both its VR and evacuation-specific functionalities. These features include: (i) capability of multiple users' immersion and active participation in the evacuation process, (ii) real-time interactivity and capability for making on-the-fly alterations of environment events and crowd-behavior parameters, (iii) capability of agents and avatars to move continuously on decks, (iv) integrated framework for both the *simplified* and *advanced* method of analysis according to the IMO/MSC 1033 Circular, (v) enrichment of the ship geometrical model with a topological model suitable for evacuation analysis, (vi) efficient interfaces for the dynamic specification and handling of the required heterogeneous input data, and (vii) post-processing of the calculated agent trajectories for extracting useful information for the evacuation process. VELOS evacuation functionality is illustrated using three evacuation test cases for a ro–ro passenger ship.

1. Introduction

A ship is a complex transportation vehicle which, in the case of passenger ships, gets more complex as a result of recent ship-building developments for cruise liners with a capacity of several thousands people on board. The safety of large passenger ships is thus becoming an increasingly important issue. In this connection and under the impact of a series of events involving large number of fatalities on passenger ships [1], the *International Maritime Organization (IMO)* has developed regulations for ro–ro[1] passenger ships, requiring escape routes to be evaluated by an evacuation analysis early in the design process [2]. To this respect, the *Maritime Safety Committee (MSC)* of IMO adopted Circular 1033, entitled *"Interim guidelines for evacuation analysis for new and existing passenger ships"* [3]. These guidelines offer the possibility of using two distinct methods of analysis: a *simplified evacuation analysis* and/or an *advanced evacuation analysis*. MSC underlines that both the methods have an interim nature and that a final method of advanced type should be reviewed in the light of the experience gained by the application of the Interim Guidelines, as well as ongoing research and development.

It is worth mentioning that the evacuation scenarios in [3] address issues related to the layout of the main escape routes and passenger demographics. However, they do not address issues arising in real emergency conditions, such as unavailability of escape arrangements (due to flooding or fire), crew assistance in the evacuation process, family-group behavior, ship-motion effects, etc. To heel such deficiencies, [3] adopts the mechanism of safety factors.

Recently, much effort has been devoted to the development of sophisticated models for performing advanced evacuation analysis of passenger ships. As a result, around 20 such models and tools are available as reported in [4,5]. A not-necessarily complete list of such tools is as follows:

1. AENEAS [6], a fast-performing simulation tool, allowing for large passenger populations.
2. Maritime-EXODUS [7], a customization of the evacuation platform EXODUS that makes use of proprietary trial data for the behavior of passengers under conditions of list and heel.
3. IMEX [8], a ship-evacuation model combining dynamics and human behavior model.
4. Evi [9,10], a multi-agent evacuation simulation software package, utilizing the *mesoscopic* approach.
5. EVAC [11], a mustering simulation program that adopts the *microscopic* approach and utilizes data and knowledge stemming from EU-funded projects.
6. BYPASS [12], a simple cellular-automaton based model.

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* Corresponding author. Tel.: +30 210 7721419; fax: +30 210 7721408.
E-mail address: kaklis@deslab.ntua.gr (P.D. Kaklis).

[1] Roll-on/roll-off (RORO or ro–ro) ships are vessels designed to carry wheeled cargo such as automobiles, trucks, semi-trailer trucks, trailers or railroad cars that are driven on and off the ship on their own wheels.
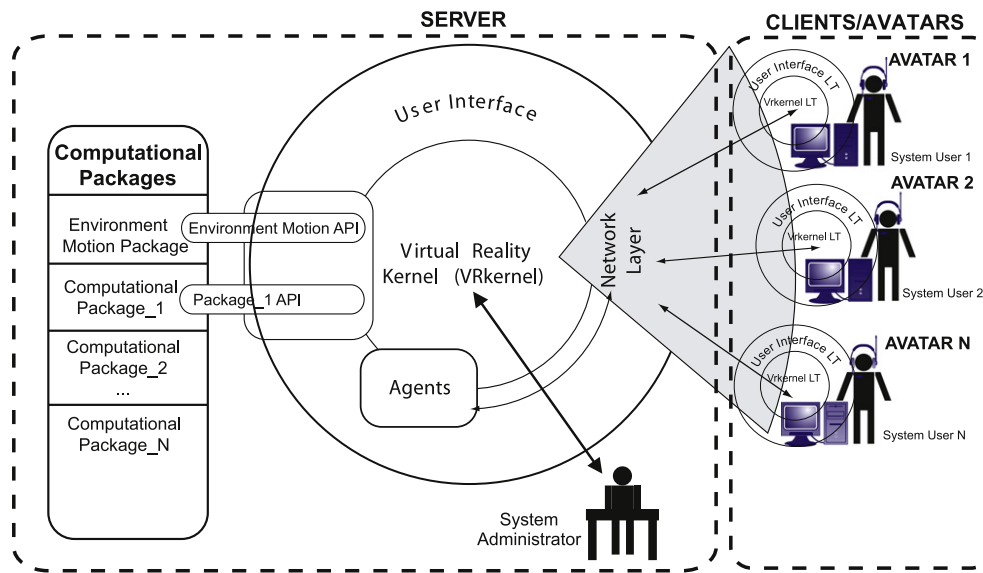
Fig. 1. The VRsystem architecture.

"Virtual Environment for Life On Ships" (VELOS) is a multi-user Virtual Reality (VR) system that supports designers to assess (early in the design process) passenger and crew activities on a ship for both normal and hectic conditions of operations and to improve the ship design accordingly [13]. VELOS is based on VRsystem [14], a generic multi-user environment with a broad range of functionalities including geometric- and VR-modeling, as well as crowd microscopic modeling through a library of nearly 20 steering behaviors. Additionally, VRsystem can communicate with computational packages, e.g., sea-keeping software for improving the environment realism and taking into account the ship-motion effect on passengers' movements. VELOS evacuation-specific functionality is greatly enhanced by the VR nature and client–server architecture provided by VRsystem, namely, the participation and real-time interaction of remote multiple users in the form of avatars. For example, avatars in the evacuation simulation may act as crew members, family-group leaders or just passengers. These VRsystem-inherited features entail a very distinctive approach to evacuation analysis in VELOS, when compared with evacuation tools in pertinent literature. In particular,

- the capability of multiple users' immersion and active participation in the evacuation process,
- the real-time interactivity and capability for making on-the-fly alterations of environment events and crowd-behavior parameters and
- the detachment from the need for discretized spaces by allowing agents and avatars to move continuously on decks,

enrich VELOS with novel and useful properties and features.

This article presents and illustrates the evacuation-specific functionality of VELOS, which, can be summarized as below:

(i) An integrated framework for both the *IMO simplified* and the *IMO advanced* method of evacuation analysis. Especially for the advanced method, we enhance IMO's approach by eliminating some important model omissions (e.g., ship motion, fire) and restrictive assumptions (e.g., simplistic crowd behaviors, full availability of escape arrangements).

(ii) Enrichment of the geometrical model of the ship with topological information in order to improve path-planning procedures.

(iii) Efficient communication through a number of interfaces that enable dynamic specification and handling of the required

input data. These data comprise passenger/crew demographics and allocation, behavioral parameters, environmental conditions (fire, flooding) as well as ship motions.

(iv) Post-processing of the fundamental output (agent trajectories) for extracting evacuation-specific information, e.g., travel-time distribution, cumulative arrival time, passenger density at specified areas.

The article is structured in the following way: Section 2 presents VRsystem, the foundation of VELOS, along with its major components and functionalities. Section 3 describes in detail the evacuation module of VELOS for both the simplified (Section 3.1) and advanced (Section 3.2) methods of evacuation analysis. In Section 4, we present and discuss the materialization, within VELOS, of three test cases for a ro–ro passenger ship: the first two deal with evacuation analysis in intact (Section 4.1) and damaged (Section 4.2) condition, while the third one exploits VELOS evacuation functionality to improve ship design (Section 4.3). Finally, Section 5 concludes with a discussion on the developed methodology, the presented results and possible routes of further enhancement.

2. VRsystem and its components

VELOS is based on *VRsystem*, [14], a generic multi-user virtual environment, that consists of mainly two modules, the server and client modules connected through a network layer. Fig. 1 provides a schematic overview of the VRsystem architecture.

As depicted in Fig. 1, users' participation in the virtual environment is carried out through the **CLIENT** module in the form of **AVATARS** enabling them to be immersed in the virtual world and actively participate in the evacuation process by interacting with agents and other avatars. On the other hand, system administrator utilizes the **SERVER** module for creating the virtual environment, setting all properties and rules for the scenario under consideration, e.g., scheduling of fire/flooding events, and awaits participants to connect to the system. The administrator's interaction may also take place during simulation phase by performing significant environment rearrangements, e.g., blockage of an escape route, system troubleshooting, etc. This twofold functionality implies the need for adopting a client/server architecture.

Based on the client–server paradigm, **Network-Layer** (see Fig. 1) is responsible for distributing any virtual world modeled and represented within VRsystem. Simultaneously, it deploys and
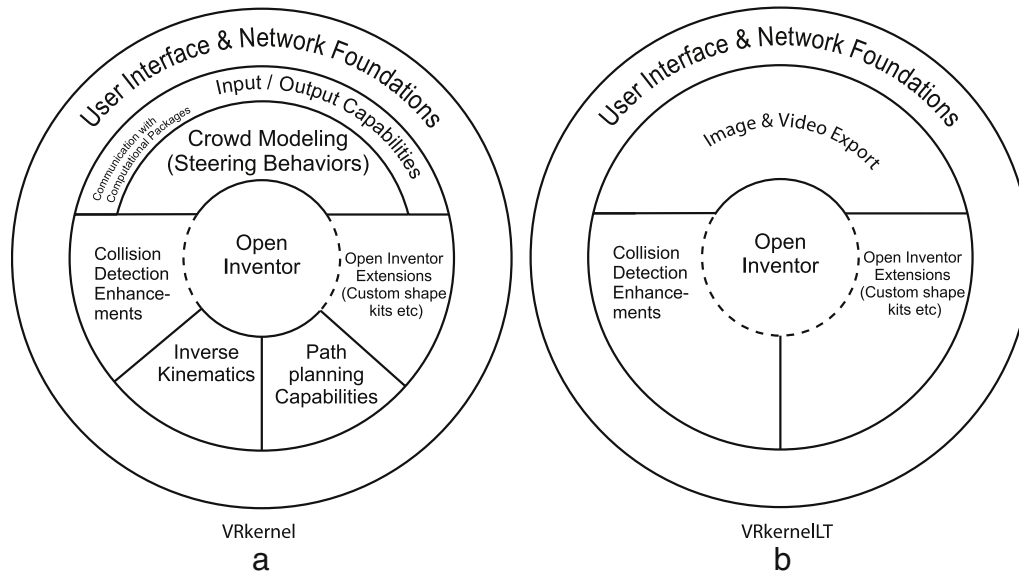
Fig. 2. Internal structure of (a) VRkernel and (b) VRkernelLT.

enacts all network services dealing with scene updates and consistency, while at the same time supports textual communication and status control for all connected avatars.

The server module comprises two major components, namely the *VRkernel* and the *User-Interface* (see in the server area of Fig. 1), while the client module has a similar structure and comprises customized versions of them, referred to as *VRkernelLT* and *User-InterfaceLT*; see in the client area of Fig. 1. These components are described in more detail in the ensuing two subsections, i.e., Section 2.1 for VRkernel and VRkernelLT and Section 2.2 for User-Interface and User-InterfaceLT.

2.1. VRkernel and VRkernelLT components

VRkernel, whose internal structure is illustrated in Fig. 2(a), is the core component of VRsystem platform in the server module; see in the server area of Fig. 1. It can be thought of as a library of objects and functions suitable for materializing the synthetic world with respect to geometric representations, collision detection, crowd modeling, motion control and simulation, event handling and all other tasks related to visualization and scene organization.

The core functionalities of VRkernel are supported by **Open Inventor** [15] (see Fig. 2), an OpenGL^{TM} based library of objects and methods used to create interactive 3D graphics applications.

Additionally, VRkernel provides an extensive set of tools for surface/solid-, illumination- and material-modeling along with algorithms for level of detail (LOD) handling. Spatial subdivision schemes as well as collision-detection engines are also part of the provided functionalities.

Crowd Modeling (Steering Behaviors) (see Fig. 2(a)) is a major part of VRkernel and in view of VELOS areas of interest (evacuation, ergonomics, comfortability), it could be considered as the most significant of its components. Crowd is modeled by adopting a microscopic approach based on individual agents and avatars. The term *agent* in VRkernel is used to describe *autonomous characters*, defined as *"autonomous robots with some skills of a human actor in improvisational theater"*; see [16]. Avatars are the system-users' "incarnation" within the virtual environment and their major difference from agents is their "controlling entity": humans for avatars vs. computer for agents.

The motion behavior of an agent is better understood by splitting it into three separate levels, namely *action selection*, *steering* and *locomotion*. In the first level, goals are set and plans are devised for the action materialization. The steering level determines the actual movement path, while locomotion provides the articulation and animation details.

Agents' autonomy is materialized within the steering level, where the steering behaviors technology is applied. Specifically, agents' autonomy is powered by an artificial intelligence structure, referred to in the pertinent literature as *mind*; see, e.g., [16,17]. The mind utilizes a collection of simple kinematic behaviors, called steering behaviors, to ultimately compose agent's motion. For each time frame, agent's velocity vector is computed by adding the previous-frame velocity vector to the mind-calculated *steering vector*. This vector is a combination of the individual steering vectors provided by each associated steering behavior in agent's mind. In mind modeling, we employ two different approaches for the steering vector calculation. The first and rather obvious one, used in *simple* mind, produces the steering vector as a weighted average of the individual ones. The second approach that takes into account priorities, called *priority blending*, is an enhanced version of the *simple priority mind* proposed in [16]. Furthermore, mind is affected, during simulation time, by *Triggers*, scene areas which, when visited by an agent, a prescribed list of actions or property changes are applied to its mind. More specifically, Triggers consist of two main components: a neighborhood definition and a list of Trigger Actions (TAs). For example, if a trigger models a sign, e.g., an exit, its neighborhood is the circular disc with radius defined by the distance, from which this sign should be visible to passengers. As for its list of actions, this would probably include a new goal setting for the steering level in agent's mind. For all supported steering behaviors there are corresponding TAs, implementing their addition or removal from an agent's mind as well as the modification of their parameters.

Nearly 20 steering behaviors have been so far implemented within VRkernel. These behaviors, partly based on the works by Reynolds [16,18,19], and Green [17], include: *Seek, Arrive, Pursuit, Flee, Evade, offset{Seek, Flee, Pursuit, Evade, Arrive}, Leader Follow, Separation, Obstacle Avoidance & Containment, Inclination, Wander, Path-following* and *Cohesion & Alignment*. This behavior set has been proven sufficient for implementing VELOS domain of interests, namely passenger comfortability, crew ergonomics and, principally, ship evacuation.

VRkernel's **Input/Output** (I/O) **Capabilities** (see Fig. 2(a)) comprise two parts: the implementation and support functions of VRkernel's native format, encoded in XML, and a data exchange library
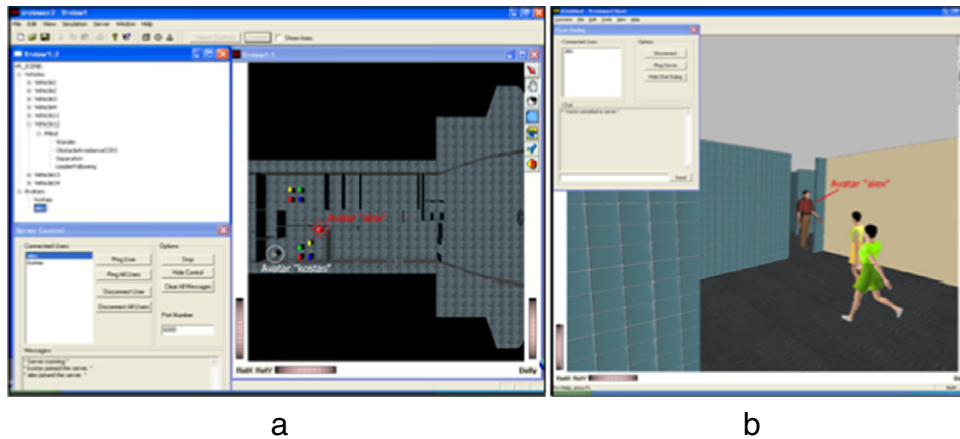
Fig. 3. Screenshots from VELOS: (a) User-Interface (b) and User-InterfaceLT.

allowing data import and export in several common geometric and VR-related file formats (IV, VRML, Autodesk's 3DS and DXF formats, STL, Biovision's BVH). Furthermore, having in mind the application areas that VELOS aims to cover, VRkernel enables **Communication with Computational Packages** (see Fig. 2(a)). Currently, in order to account for the ship-motion effect on passenger's movement, VRkernel interpolates pre-computed calculations from seakeeping codes, e.g., SWAN [20].

Coming now to the client module structure (see in the client area of Fig. 1), the **VRkernelLT** component (see Fig. 2(b)) does not require the crowd-modeling, inverse-kinematics and path-planning functionalities as these are implemented in the server module. Furthermore, I/O capabilities are limited to image and video export. On the other hand, participant's immersion requirement in the virtual world dictates enhanced graphics capabilities for VRkernelLT.

2.2. User-Interface and User-InterfaceLT components

VRsystem's user interface comprises two interfaces, one for the server (User-Interface) and one for the client applications (User-InterfaceLT); see Fig. 1.

As shown in Fig. 3(a), **User-Interface** comprises four main components, namely the *Application Framework*, containing all menu and toolbar items, the *Rendering View* (graphics area in the right part in Fig. 3(a)), the *Tree View* of the environment objects (upper-left part in Fig. 3(a)) and, finally, the *NetServer User-Interface Dialogue;* see in the lower-left part of Fig. 3(a).

User-InterfaceLT (Fig. 3(b)) comprises three main components. Besides the Application Framework, the most important component of this interface is the Rendering View, which is the user's window on the virtual world, where user's interactions are carried out. This component is endowed with keyboard and mouse event handlers, so that the user can control avatar's movements. The third, and final, component is the *Network Control Dialogue* (upper-left corner in Fig. 3(b)), which gathers all options and controls for handling the network connection with the server part of VRsystem.

It is worth noticing that both interfaces share a common look-and-feel (cf. Fig. 3(a) with (b)) but provide different options and functionality customized to their underlying applications. For example, "open" in the Application Framework of User-Interface retrieves a stored synthetic world, whereas "open" in the Application Framework of User-InterfaceLT initiates a network connection with the server.

3. Evacuation analysis in VELOS

VRsystem provides the basis for developing VELOS platform that aims to enable researchers and designers to assess passenger and crew activities and improve ship design accordingly. In this section, we shall present the evacuation analysis module of VELOS. To this respect, we refer to IMO MSC/Circular 1033 presenting guidelines for the implementation and assessment of evacuation analysis. These guidelines offer two methods of analysis: the IMO simplified (Section 3.1) and the IMO advanced method, as described in [3, Annexes 1 and 2 respectively]. Coarsely speaking, IMO simplified method is deterministic, with passenger movement being modeled through a simple hydraulic scheme. On the contrary, IMO advanced method is of statistical nature, adopting a microscopic approach to model passenger movement. Although this method is more realistic, both the IMO methods are subject to restrictive assumptions and omissions, e.g., ship-motion, fire/smoke influences are not taken into consideration. These restrictions (see items 5a–e in Table 1) are removed in VELOS implementation of the advanced method, henceforth referred to as *VELOS advanced method* (Section 3.2).

Table 1 summarizes the goals, basic assumptions, typical benchmark scenarios and performance standards of the two IMO methods.

We now present the basic novel elements/functionalities of VELOS concerning the materialization of evacuation analysis:

(i) A topological model suitable for evacuation analysis: The hydraulic network needed in IMO simplified method as well as passengers' path planning and fire effluent, needed for the VELOS advanced method, require space connectivity information for their materialization. In VELOS, this information is provided through a topological structure, attached to ship's geometrical model. For coding and saving the required topological information, a graph $G = (V, E)$ is created with V/E denoting the set of nodes/edges of the graph. In our case the set V comprises spaces, e.g., public spaces, cabins and corridors, while the set E consists of the architectural and outfitting means used for connecting the aforementioned spaces, e.g., doors, staircases and elevators. The so resulting graph will be referred to as the *space graph*; the lower half of Fig. 4 depicts the space graph for the general arrangement plan illustrated in the upper half of it.

The space graph is materialized through an interface comprising two viewports, the *RenderView* (Fig. 5(a)) and the *GraphView* (Fig. 5(b)). Both viewports provide space graph with creation and editing capabilities, but adopt different representation approaches. RenderView enables the user to create the graph by working directly on the geometrical model, covering each space with a transparent box (see Cabi, $i = 1, 2, 3, 4$ in Fig. 5(a)) or a collection of transparent boxes (see Corridor_Parti, $i = 1, 2$ in Fig. 5(a)). In the sequel, by simply drawing line segments connecting the constructed boxes, the user creates connections between them. The above construction automatically generates in GraphView an abstract representation of the space graph using spheres and rods

Table 1
IMO evacuation analysis methods.

IMO Advanced Method	IMO Simplified Method

• **Goal**: To assess ship performance by using simulation of actual evacuation procedure in emergency conditions applied to typical benchmark scenarios.
 	
• **Basic assumptions**
 	
1. The passengers and crew are represented as unique individuals with specified individual abilities and response times;
 	
2. Passengers and crew will evacuate via the main escape routes, as referred to in regulation II-2/13 of the *International Convention for the Safety of Life at Sea* (SOLAS), 1974 ;
 	
3. Passenger load and initial distribution is based on chapter 13 of the *International Code for Fire Safety Systems* (FSS Code, Resolution MSC.98(73));
 	
4. Unless otherwise stated, full availability of escape arrangements is considered;
 	
5. A safety margin is included in the calculation to take account of model omissions, assumptions, and the limited number and nature of the benchmark scenarios considered. These issues include:
 	
  a. The crew will immediately be at the evacuation duty stations ready to assist the passengers;
 	
  b. Passengers follow the signage system and crew instructions (i.e., route selection is not predicted by the analysis);
 	
  c. Smoke, heat and toxic fire products present in fire effluent are not considered to impact passenger/crew performance;
 	
  d. Family group behavior is not considered in the analysis; and
 	
  e. Ship motion, heel, and trim are not considered.
 	
• **Typical Scenarios**
At least the same scenarios as in the simplified method.
• **Performance standards**
A+T+2/3(E+L)<n
A: awareness time (A=10 min in night case, A=5 min in day case)
T: calculated travel time
E: embarkation time
L: launching time
n=60 min for ships with no more than 3 vertical zones
  80 min for ships with more than 3 vertical zones
	• **Goal:** To assess ship performance by using a basic in nature method applied to typical benchmark scenarios.
	
	• **Basic assumptions**
	
	1. All passenger and crew will begin evacuation at the same time and will not hinder each other;
	
	2. Passengers and crew will evacuate via the main escape routes, as referred to in SOLAS regulation II-2/13;
	
	3. Initial walking speed depends on the density of persons, assuming that the flow is only in the direction of escape route and that there is no overtaking;
	
	4. Full availability of escape arrangements is considered;
	
	5. Counter flow is accounted for by a relevant factor;
	
	6. Effects of ship motions, passenger age and mobility impairment, unavailability of corridors, restricted visibility due to smoke are accounted for in a safety factor.
	
	• **Typical Scenarios**
	Case 1 (night): Passengers in cabins with maximum berthing capacity fully occupied; members of the crew in cabins occupied to 2/3 of maximum berthing capacity; service spaces occupied by 1/3 of the crew.
	Case 2 (day): Passengers in public spaces occupied to 3/4 of maximum capacity; members of the crew in public spaces occupied to 1/3 of the maximum capacity; service spaces occupied by 1/3 of the crew; crew accommodation occupied by 1/3 of the crew.
	Case 3 (night): The main vertical zone with the longest travel time is investigated. The initial population distribution is as in Case 1. One of the following two alternative scenarios should be considered. Alternative 1: Only 50% of the stairways capacity is considered. Alternative 2: 50% of the persons of the neighboring vertical zone are forced to move and proceed towards the muster station through this zone.
	Case 4 (day): The same scenario as in Case 3 but with initial population distribution as in Case 2.
	
	• **Performance standards**
	The same as in the advanced method.

for nodes and edges, respectively; see Fig. 5(b). Alternatively, the user can create the space graph by working directly on GraphView. Nevertheless, this approach is less intuitive for the user has to provide geometrical information, such as position and dimension of the spaces, which is readily extracted when working on RenderView.

(ii) Efficient preparation of the required input data: In order to materialize an evacuation scenario the user has to specify, apart from the geometrical and topological model, environmental and passenger data. VELOS provides an interface for dynamically specifying a variety of environmental data such as: day/night condition, fog/smoke/fire occurrence, ship motions corresponding to user-defined navigational and sea conditions, etc. Regarding passenger data, VELOS provides an interface for defining passenger/crew categories, allocating to each one a statistical profile for the parameters of their behavioral model and locating them initially in space, according to the considered scenario. The passenger-data interface

offers two options: an interactive, where the user categorizes passengers and locates them in selected spaces, and an automatic one, where passengers are categorized according to IMO [3] and distributed randomly. It is worth noticing that the definition of input data is dynamic in the sense that they can be defined/redefined during the execution of an evacuation scenario, affecting in this way both the topological model of the ship (by, e.g., changing the availability of a space due to flooding) and the behavioral model of the agents (by, e.g., decreasing/increasing the agent visibility due to smoke). A more detailed description of the developed interfaces is given in the subsequent subsections.

(iii) Exploitation of the output information: The fundamental output of VELOS, when using the VELOS advanced method of analysis, comprises agent trajectories, considered as space curves parameterized with respect to time t; see Fig. 6.

By means of post-processors built within VELOS we can exploit these results in order to extract the following output:
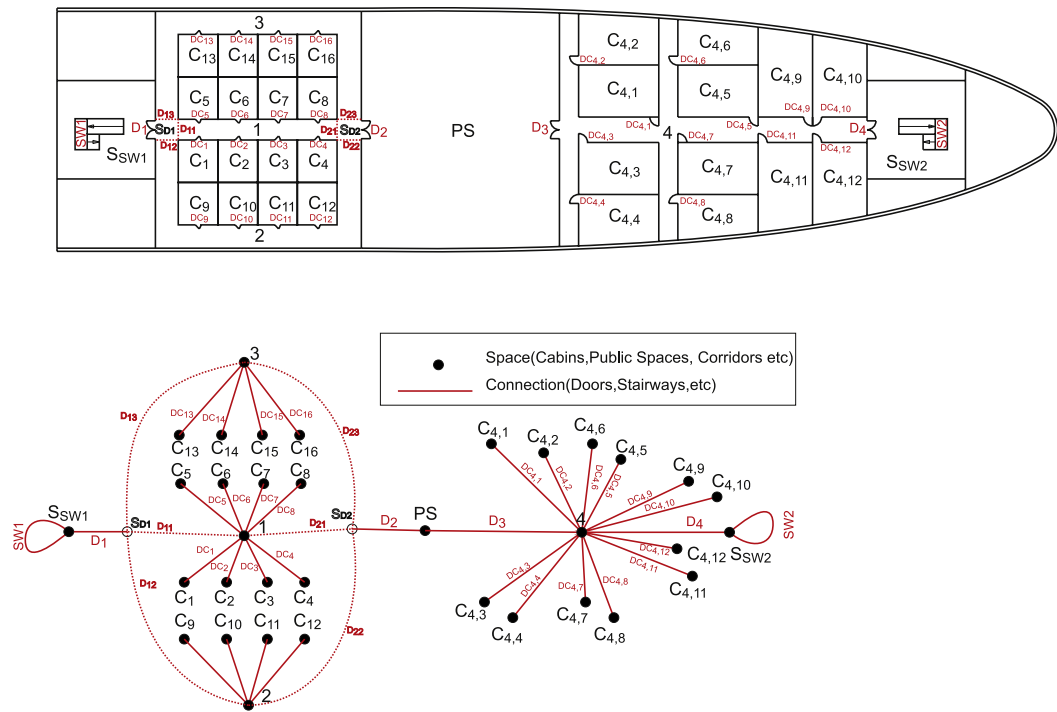
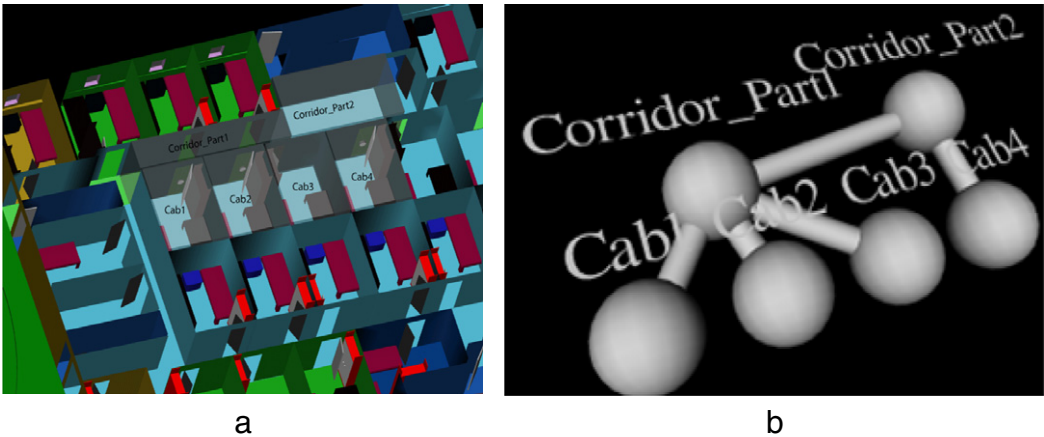**Fig. 4.** Space graph of a general arrangement plan.

Fig. 5. (a) RenderView: topological model for 4 cabins and (b) GraphView: abstract representation of RenderView.
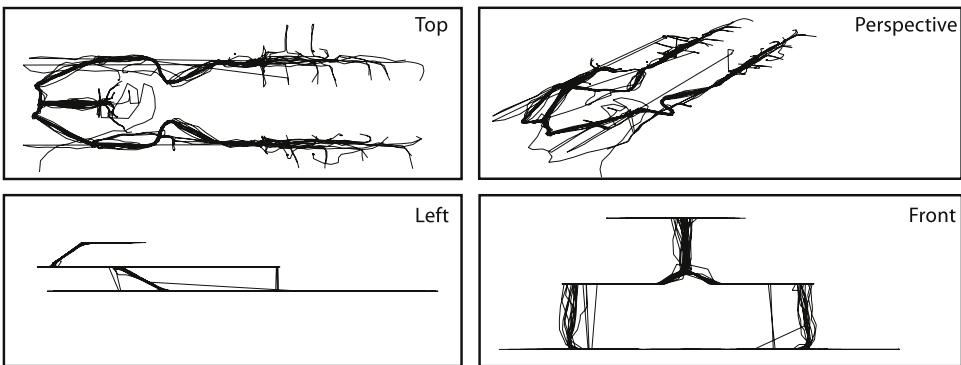

Fig. 6. Agent trajectories.

- The total travel time, that is the time needed for all passengers to reach the muster station; see Fig. 11.
- Number of passengers reaching muster station versus time; see Fig. 12.
- Passenger densities at specified locations; see Fig. 13. This information permits the user to identify congestion points and critical areas, which may require design modification.

Furthermore, since each scenario is simulated many times, VELOS is able to perform statistical analysis of the output, providing information such as average travel time, travel-time distribution, etc.

In the case of the simplified method of analysis, the output of VELOS comprises integrated results, i.e., total evacuation time and congestion points. For completeness and responding to IMO's requirement, tools have been developed within VELOS providing schematic representations of the analyzed ship areas and details of the calculations in tabular form; see Tables 3 and 4.

The use of the above-mentioned functionalities of VELOS, specific to evacuation analysis, is illustrated in test cases presented in Section 4. In the sequel, we present the way that both the simplified and advanced methods of evacuation analysis are implemented within VELOS.

3.1. IMO simplified method as implemented in VELOS

According to the simplified method (see right column in Table 1), the escape routes are considered as a hydraulic network, where the pipes are the corridors and stairways, the valves are the doors and other restrictions in general and the tanks are the public spaces and the cabins. The speed of persons along an escape route depends on the type of the escape facility (stairs, corridors) and the specific flow of persons in the route involved, which is defined as the number of escaping persons per unit time, per unit width. Almost all data and parameters needed for the application of the method are based on the documented data resulting from civil building experience.

In the context of VELOS environment, the realization of an evacuation scenario using the simplified method exploits the topological model constructed using the relevant VELOS functionality (see (i) in the introductory part of this section). More precisely, using the space graph of the ship and the functions associated to it, we produce trees, each tree corresponding to a muster station of the vertical zone analyzed and consisting of all escape paths leading to it. Since these paths have to follow the main escape routes of the ship, the path connecting any point on board ship to a muster station is unique and, in this way, the union of all these paths constitutes a tree. After constructing the trees corresponding to all muster stations of the vertical zone considered, the procedure for applying the simplified method can be outlined as follows:

1. Distribute passengers/crew to tree nodes according to the scenario considered (automatically or interactively).
2. Calculate, by applying the adopted hydraulic model on the tree, the flow time t_i from each occupied node to the root node (muster station).
3. Calculate the so-called Travel Time $T = \max\{t_i\} * \text{safety\_factor}$.
4. Repeat steps 1–3 for all trees (muster stations).
5. Check the performance standard given in Table 1 with respect to max T.
6. Post-process the results and create documentation; see (iii) in the introductory part of this section.

3.2. VELOS advanced method of evacuation analysis

VELOS advanced method materializes all the specifications of IMO advanced method and offers numerous additional functionalities in order to remove the restrictive assumptions and omissions pointed out in items 1–5 in the left column of Table 1. In the sequel, we summarize the functionalities of VELOS advanced method in correspondence with this itemization:

1. As already noted in Section 2, VRkernel enables crowd modeling via autonomous agents, developed on the basis of steering-behavior technology. The personality of each agent is configured through a plethora of dynamically assigned parameters, leading to realistic behavioral models for passengers, specific passenger groups, e.g., families and crew, on a microscopic level.
2. Passengers and crew can evacuate via specified escape paths, e.g., those referred to in SOLAS regulation II-2/13, or, in a more realistic setting, by appealing to the path-planning functionality offered by VELOS. This functionality is based on Dijkstra's algorithm [21,22], applied upon the space graph (see (i) in the introductory part of this section) for obtaining a rough path between spaces. In order to take into account the interior layout of each space, this path is further refined with the aid of A* algorithm [23]. Path planning is of dynamic character subject to events, e.g., smoke, fire, flooding, that can alter the topological graph of the ship, thus implying the need for recalculating the evacuation path. Even more, path following may be abandoned due to the activation of the leader-follow behavior when, e.g., passengers meet crew members.
3. Regarding passenger load and initial distribution associated to each scenario, VELOS provides two alternative ways: an automatic method that distributes passenger load in the available spaces randomly and an interactive one, where the user chooses passengers from the available groups and locates them in selected spaces. As far as the internal structure of the initial passenger load is concerned, the interface permits to define groups of passenger and crew members that are associated with a different statistical profile for a variety of important parameters in their behavioral model. The default choice is as described in [3] and consists of 12 different groups possessing different behavioral models that are horizontally classified according to gender, age and moving ability. Each group is endowed with min/max speed limits for walking as well as stairways descending/ascending. These limits are subsequently used for creating statistical distributions of basic parameters of the behavioral model, e.g., maximum speed, maximum applied force, etc. VELOS user can select between different types of distribution (e.g., uniform, normal) for different groups. Finally, each group can be associated with a different color for evacuation monitoring.
4. Availability of escape arrangements can be treated dynamically when events may decrease the capacity or eliminate the availability of some escape routes.
5. Model omissions and restrictive assumptions that imply the need for introducing a safety factor in the IMO advanced evacuation analysis, have been removed in VELOS, as described in detail below:
   5a. In VELOS, it is not necessary to locate crew, when starting the evacuation analysis, at the evacuation duty stations for assisting passengers. On the contrary, crew members can be located at any place and appealing to the path-planning functionality move towards their evacuation duty sites. More importantly, crew members can be human controlled through the avatars mechanism.
   5b. Passengers follow the signage system and crew instructions, whenever available; otherwise, they can find their own way towards muster stations by appealing to general steering behaviors, environment triggers and/or path-planning functionality.
   5c. VELOS permits passengers/crew to be influenced by smoke, heat and toxic fire products that are present in fire effluent. This is achieved by:
      - importing pre-computed time-series of fire products, according to different methods for calculating fire growth and smoke spread in multiple compartments; see, e.g., [24,25],

Table 2
Pseudo-code for simulating fire influence on agents.

```
1.   Choose the fire data file
2.   Wait for fire activation
3.   Activation of fire event at t=t_o
        a.  Create fire triggers at the points referred to in fire data file
        b.  Add action for decreasing the health index of agents lying within the range
            of influence of fire triggers
        c.  Add action for path-finding recalculation of agents lying within the range
            of influence of fire triggers
4.   For all t>t_o:
        a.  For every space possessing fire data
             I.  Change space color according to the fire data corresponding to time
                 t
        b.  For every trigger from the set of fire triggers
             I.  Update for possible decrease of health index of agents (FUNCTION A)
            II.  Update if it is required recalculation of path finding (FUNCTION B)
                  i.  For every agent inside the trigger
                      a)  Decrease health-index
                      b)  If recalculation of path finding is required:
                          Calculate new path towards muster station


----------------------------------------------------------------------

FUNCTION A: health-index decrease(t) =
f(a*Temperature(t)+b*Co_concetration(t));

FUNCTION B: If, for a space belonging in the agent path towards muster station, space-
availability is changed proceed to path recalculation.
```

- setting time of fire explosion before, simultaneously or after the evacuation starting time,
- modeling the influence of fire products on the behavioral model of agents with the aid of an algorithm, whose pseudo-code is outlined in Table 2,
- visualizing the fire products in the synthetic world.

5d. VELOS is enriched with family-group behavior by creating groups possessing family structure and attributing the *leader-follow* behavior to children/parents versus parents/crew, respectively.

5e. Advanced evacuation analysis in VELOS is combining the availability of ship-motion data with the so-called *Inclination* behavior that has been introduced as a simple means for considering the effect of ship motion on agent's movement. Pre-computed ship-motion history is imported in VELOS through a suitable series of interfaces. Inclination behavior resembles in definition and effect the influence of a gravity field that would hinder agent motion accordingly. Specifically, we consider a static global force-vector $\mathbf{g}$ normal to deck's plane in the upright position of the ship. If the deck deviates from its upright position (i.e., non-zero heel, and/or trim, angles), the projection of $\mathbf{g}$ on it will obviously acquire a non-zero value $\mathbf{g}_p$, which forms Inclination's steering vector $\mathbf{v}_i$ as follows: $\mathbf{v}_i = \lambda(\omega)\mathbf{g}_p$, where ω is the angle formed between $\mathbf{g}$ and the normal to the deck plane. Inclination behavior is active when ω lies between two threshold angles: the lower threshold is used to discard plane motions with negligible effect on agent's motion, while values above the upper threshold lead to movement inability, as the limit of agent's balancing capabilities is surpassed. Threshold angles and the weight function $\lambda(\omega)$ are defined via experimental data; see, e.g., [26,27]. An application of this behavior is demonstrated in test case 4.2 of Section 4.

After describing the novel features of VELOS advanced method, we outline the underlying method in the form of pseudo-code; see Table 3.

We end this subsection by referring to verification/certification issues of VELOS advanced method. VELOS software has been successfully verified against three of the four components proposed by IMO in [3, Annex 3] for verifying/certifying software packages for evacuation simulation, as analyzed in the sequel:

1. **Component verification**: It involves checking that the various components of the software perform as intended. This has been justified by benchmarking VELOS module through a battery of seven elementary test scenarios proposed in [3, Annex3].
2. **Functional verification**: VELOS reference manual describes in a comprehensible manner the complete range of model capabilities and inherent assumptions and gives a guide to the correct use of these capabilities.
3. **Qualitative verification**: VELOS advanced method has been successfully checked, as proposed in [3, Annex 3], by benchmarking through four test scenarios (Tests 8–11), which assures its qualitative verification, as well. In the sequel, we present the results obtained by VELOS for two of these test scenarios:

   Test 8: *Counterflow — two rooms connected via a corridor*
   Two rooms connected via a corridor (Fig. 7(a)) are used for the computation of the time needed for 100 persons in Room 1 to travel to Room 2, while 0, 10, 50 and 100 persons from Room 2 are simultaneously moving in the opposite direction, trying to travel to Room 1. The expected result, as specified in [3], is that the recorded time increases with the number of persons in counterflow. Fig. 7(b) depicts the recorded time for four simulation runs for each of the counterflow alternatives and verifies the expected relation between counterflow increments and travel-time prolongation.

   Test 9: *Exit flow — crowd dissipation from a large public room*
   This test examines the crowd dissipation and exit from a public room (Fig. 8(a)) with 1000 persons uniformly distributed in it. Simulations times are recorded in two cases: with all four exits available and when two of them are blocked. The expected result in this case is that the exit time should be approximately doubled when half of the exits become unavailable. This result is verified with VELOS as can be seen in Fig. 8(b).

Table 3
Pseudo-code for the VELOS advanced method of evacuation.

```
A. Define/Import geometrical data and associated topological model
B. Define/Import crowd (passengers and crew) demographics
   Define for each agent/group its behavioral model accordingly
C. Define/Import evacuation scenario and distribute crowd accordingly
D. Define/Import ship-motion and fire-simulation data


E. Simulation Loop: For each time frame:
   1. If sea state is not calm:
         Calculate current heel and trim deck angles
         Pass data to agents' inclination steering behavior
   2. If fire simulation is active, then using the algorithm outlined
      in Table 2:
         Calculate current Fire Data
         Update crowd health-index decrease for fire-occupied spaces
         Visualize fire Data
         If current fire conditions affect spaces' availability:
               Find passengers affected
               Recalculate paths to muster station
   3. Perform crowd simulation:
         3.1 Perform all trigger-actions to agents in trigger areas
         3.2 For each connected avatar:
               Update position/orientation and representation
         3.3 For each agent:
               Calculate steering vector
               Update positions and orientations
   4. For connected avatars:
         Send scene update to client application
   5. Save avatars' and agents' current positions and simulation time
   6. If all evacuees reach muster stations: Exit simulation loop.
```
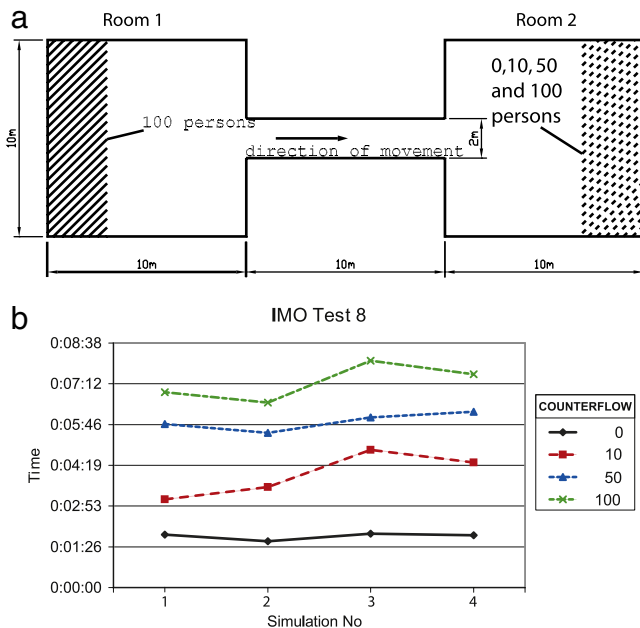

Fig. 7. (a) IMO Test 8 rooms' arrangement and (b) VELOS recorded simulation times.

4. **Quantitative verification**: This component involves the comparison of VELOS with reliable data generated from evacuation demonstrations. At the time of publication of [3], there were insufficient reliable experimental data to allow a thorough quantitative verification of egress models. IMO's recommendation is that until such data are available, the first three components of the verification process should be considered sufficient.
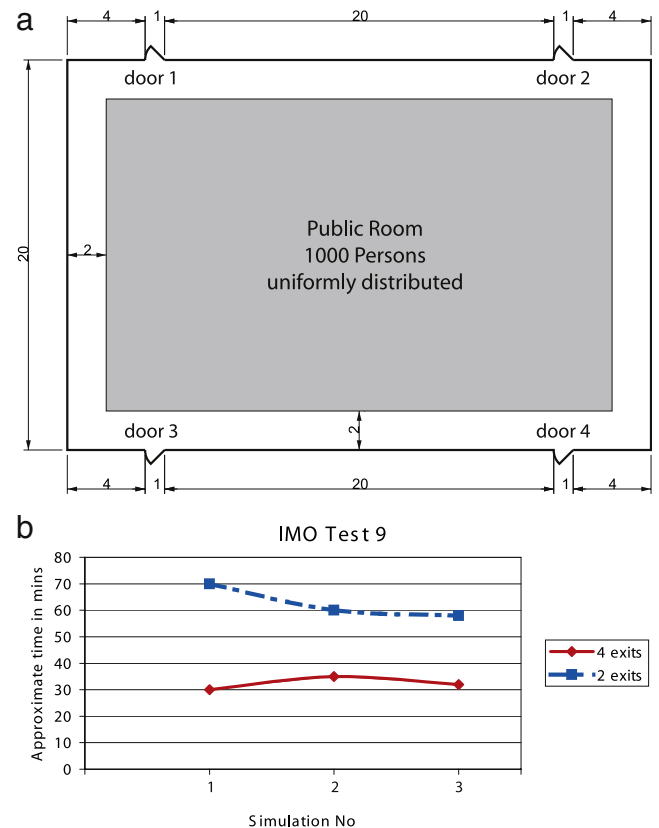
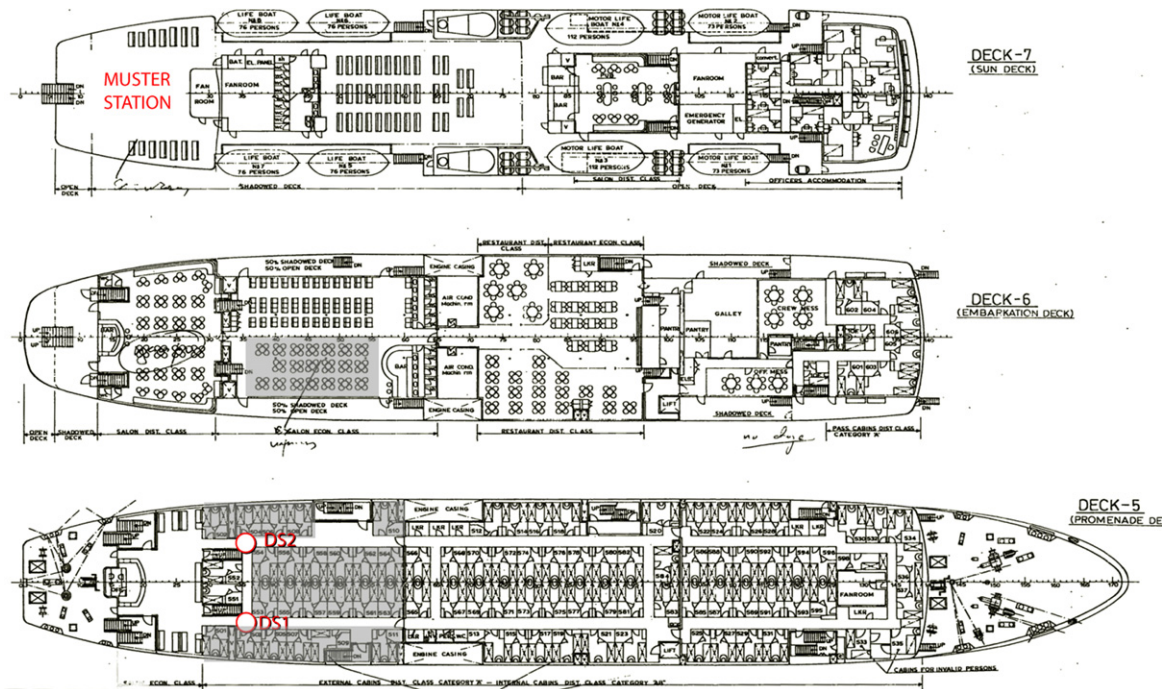Fig. 8. (a) IMO Test 9 arrangement and (b) VELOS recorded simulation times.

Fig. 9. General arrangement and passengers' distribution at the aft. vertical zone.

4. Testing VELOS for a ro–ro passenger ship

In this section, we shall use VELOS for performing evacuation analysis for a ro–ro passenger ship, employing both the simplified and the VELOS advanced method of analysis. The general arrangement of the selected ship is depicted in Fig. 9. The passengers are located on Decks 5 and/or 6 of the after vertical zone, while Muster Station is located on Deck 7. Three test cases are presented: the first one performs evacuation analysis for a typical scenario in intact condition, using both the simplified and VELOS advanced method; the second one deals with the evacuation analysis in damaged condition using VELOS advanced method, while the third one exploits the simplified method in order to propose design improvements for the ro–ro passenger ship.

4.1. Evacuation analysis in intact condition

Scenario: 60 passengers are located in the cabins of Deck 5 and part of the public spaces on Deck 6; see gray areas in Fig. 9. The scenario is considered in daylight condition.

4.1.1. VELOS advanced method

Population demographics are as proposed in [3]. For every simulation run, we distribute randomly the population in the aforementioned areas. The scenario was simulated 80 times. Snapshots from an instance simulation are given in Fig. 10. We compute the travel time required for all the passengers to reach Muster Station as well as passenger density for a pair of selected areas, depicted as DS1 and DS2 in Fig. 9.

Fig. 11(a) depicts travel time (bullets) for each simulation run along with the average travel time t_{av} (solid line) for all runs, which is equal to 136 s. In Fig. 11(b), the distribution of the travel time for the simulation runs is presented.

Fig. 12(a) shows, for each simulation run (corresponding to a different color), the percentage of passengers reaching Muster Station for each time unit, a quantity which will be hereafter referred to as the *cumulative arrival time* at Muster Station. The minimum/maximum envelope of the function set in Fig. 12(a), as well

as their average function are depicted in Fig. 12(b). The smoothness of the average function is an indication that the total number of simulation runs (80 in our case) is adequate for estimating the travel time. These results are also in compatibility with the estimated average travel time t_{av}, since, as one can easily check from Fig. 12(b), for $t = t_{av} = 136$ s more than 98% of the evacuees have reached Muster Station.

Finally, Fig. 13 illustrates the maximum and average passengers' density distributions with respect to time, for the selected areas DS1 and DS2 (Fig. 9) for all simulation runs. The average density distribution is obviously a less smooth function, when compared with the average cumulative arrival time (Fig. 12(b)), which may be attributed to their different nature: density distribution in a specific area is a quantity of local character, while the number of evacuees reaching Muster Station is a quantity of integral character for the evacuation process. In this way, we could say that quantities of local character need more simulation runs to converge to their mean value, which characterize the evacuation process. In Fig. 13, one can also observe that, although there are simulation runs that exhibit congestion in the areas DS1 and DS2, i.e., density becomes greater than four persons/m², the mean density remains well below the congestion limit, implying that in these areas we should not expect congestion.

4.1.2. Simplified method of analysis

Tables 4 and 5 constitute a fragment of the output provided by VELOS when employing the simplified method of analysis. We see that the highest travel time to the Muster Station max t_i is 178.4 s and, using the safety factors proposed in [3], travel time T becomes 410.3 s; see Table 4. As shown in Table 5, congestion takes place at both areas DS1 and DS2 (Fig. 9).

In order to compare the simplified with the advanced method, we have to examine the net travel times, namely the highest travel time max $t_i = 178.4$ s for the simplified method (Table 4) with the average travel time $t_{av} = 136$ s for the advanced method (Fig. 11(a)), without using any safety factor. In this context, we observe that the simplified method overestimates the net travel time. Furthermore, regarding the occurrence of congestion in areas
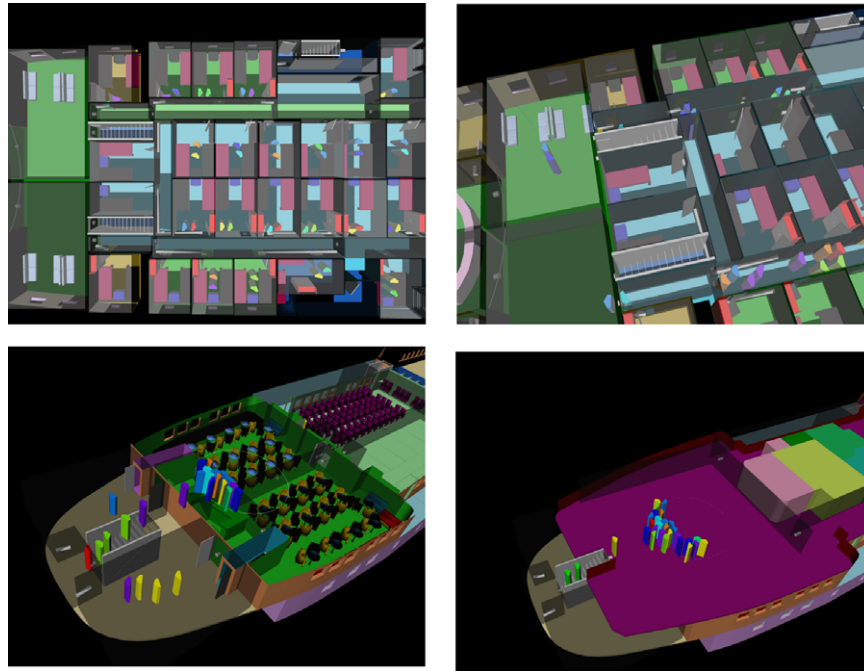
Fig. 10. Snapshots from VELOS rendering area during an evacuation simulation in test case 4.1.

Table 4
Escape-time calculations.

Escape route on	T_{deck}	t_f	t_{stair}	$t_{assembly}$	t_i	T
Deck 5	27.95	113.64	17.83	18.98	178.4	**410.3**
Deck 6	0.00	113.64	7.53	18.98	140.1	**322.3**
Deck 7	0.00	0.00	0.00	18.98	19.0	**43.7**

DS1 and DS2, the simplified method gives again more conservative predictions, foreseeing queue formation at both the sites (cf. Table 5 versus Fig. 13). Nevertheless, the two methods agree qualitatively in the sense that the advanced method predicts higher average density at DS1 when compared with DS2 (Fig. 13), while the simplified method predicts higher specific flow at DS1 when compared with DS2 (third column in Table 5).

4.2. Evacuation analysis in damaged condition

We utilize the same scenario as in Case 4.1 with the sole exception that the ship is assumed to be in a damaged condition, exhibiting a constant heel angle of seven degrees. This condition is chosen, since the IMO advanced method cannot differentiate between intact and damaged conditions, as the effect of inclination (heel in our case) is not taken into consideration; see Table 1, left column, item 5e.

In the context of applying VELOS advanced method, the scenario was simulated 12 times and the calculated average travel time t_{av} is 187 s. As expected, t_{av} is larger (approx. 35%) than the corresponding one (136 s) for the intact condition. Regarding the simplified method, we note that, being invariant with respect to ship inclination, its application here would yield the same results as in the intact case. In this connection, it is worth noticing that, for the case of ship with inclination, the advanced method provides a

larger average travel time when compared with that obtained from the simplified one. Finally, Fig. 14(a) depicts the cumulative arrival time at Muster Station for each simulation run, while Fig. 14(b) depicts the minimum, maximum and average of the cumulative arrival time for all runs.

4.3. Design for evacuation

In this case, we employ the simplified method to illustrate VELOS capabilities as a design tool for improving ship evacuation. For this purpose, we consider the same ship configuration (Fig. 9) with a passenger population of 150 persons initially situated in Deck 5 cabins. For this case, the simplified analysis gives a travel time T equal to 546.7 s. As it can be readily seen in the output Table 6, queue is formed both at the entry and exit of the stairway leading from Deck 6 to Muster Station on Deck 7 (Fig. 15).

A simple approach for handling the queuing problem is to widen the stairway width. Originally, the width was 1 m, which was then increased to 1.5 m. This modification resulted in removing queuing at the stairway entry, whereas queue was still forming at its exit (Table 7). Furthermore, T was significantly reduced to 418.7 s. The minimum width for which the remaining queue disappears is 2.0 m (see Table 8). In this case, the calculated travel time T is 414.4 s. If we further widen the stairway, travel time T remains unchanged and thus this width can be considered as optimal with respect to the travel time.

5. Conclusions & future work

In this work, we presented VELOS platform, a multi-user VR system, which aims to support designers, early in the design process, as well as trainers to enhance crew performance in hectic conditions, thereby significantly improving ship safety. Although

Table 5
Flow calculations.

| Name	Persons	S. Flow	MAX SF	S. Flow	C. Flow	Speed	Queue
Deck 5 corridor where DS2 is placed	20	3.04	1.30	1.30	1.30	0.67	YES
Deck 5 corridor where DS1 is placed	24	3.63	1.30	1.30	1.30	0.67	YES

Table 6
Flow calculations for Deck 6; stairway width 1 m.

Name	Persons	S. Flow	MAX SF	S. Flow	C. Flow	Speed	Queue
Deck 6 space before stairs right	101	0.88	1.30	0.88	0.88	N.A.	NO
Deck 6 space before stairs left	49	0.88	1.30	0.88	0.88	N.A.	NO
Deck 6 stairway entry	**150**	**1.76**	**1.30**	**1.30**	**1.30**	**N.A.**	**YES**
Deck 7 stairway exit	**150**	**1.30**	**0.88**	**0.88**	**0.88**	**0.44**	**YES**
Travel Time: 546.7 s							

Table 7
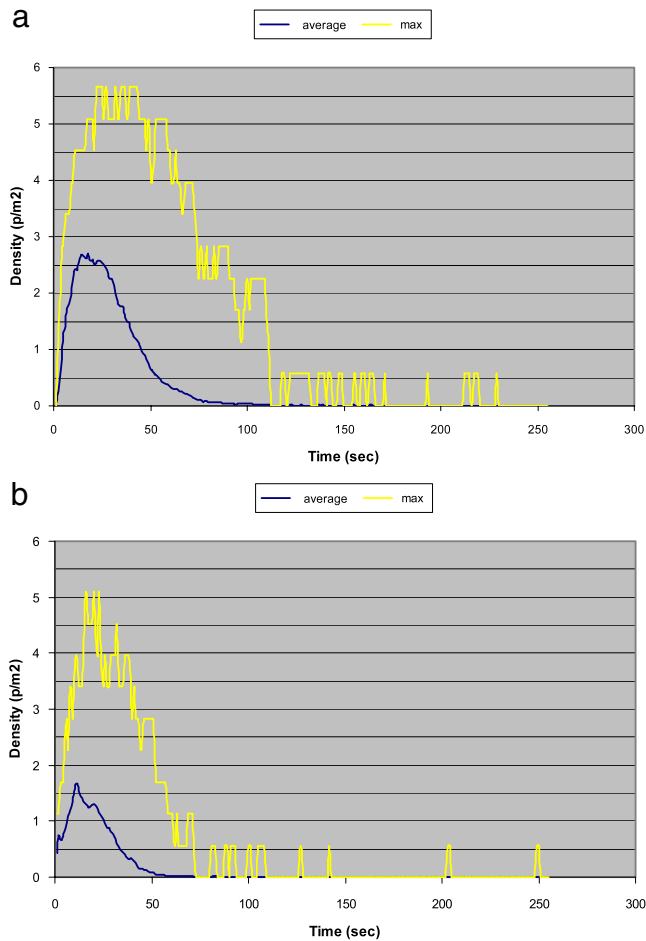Flow calculations for Deck 6; stairway width 1.5 m.

Name	Persons	S.Flow	MAX SF	S.Flow	C.Flow	Speed	Queue
Deck 6 space before stairs right	101	0.88	1.30	0.88	0.88	N.A.	NO
Deck 6 Space Before Stairs Left	49	0.88	1.30	0.88	0.88	N.A.	NO
Deck 6 stairway entry	**150**	**1.17**	**1.30**	**1.17**	**1.76**	**N.A.**	**NO**
Deck 7 stairway exit	**150**	**1.17**	**0.88**	**0.88**	**1.32**	**0.44**	**YES**
Travel Time: 418.7 s							

Table 8
Flow calculations for Deck 6; stairway width 2 m.

Name	Persons	S.Flow	MAX SF	S.Flow	C.Flow	Speed	Queue
Deck 6 space before stairs right	101	0.88	1.30	0.88	0.88	N.A.	NO
Deck 6 space before stairs left	49	0.88	1.30	0.88	0.88	N.A.	NO
Deck 6 stairway entry	**150**	**0.88**	**1.30**	**0.88**	**1.76**	**N.A.**	**NO**
Deck 7 stairway exit	**150**	**0.88**	**0.88**	**0.88**	**1.76**	**0.44**	**NO**
Travel Time : 414.4 s							
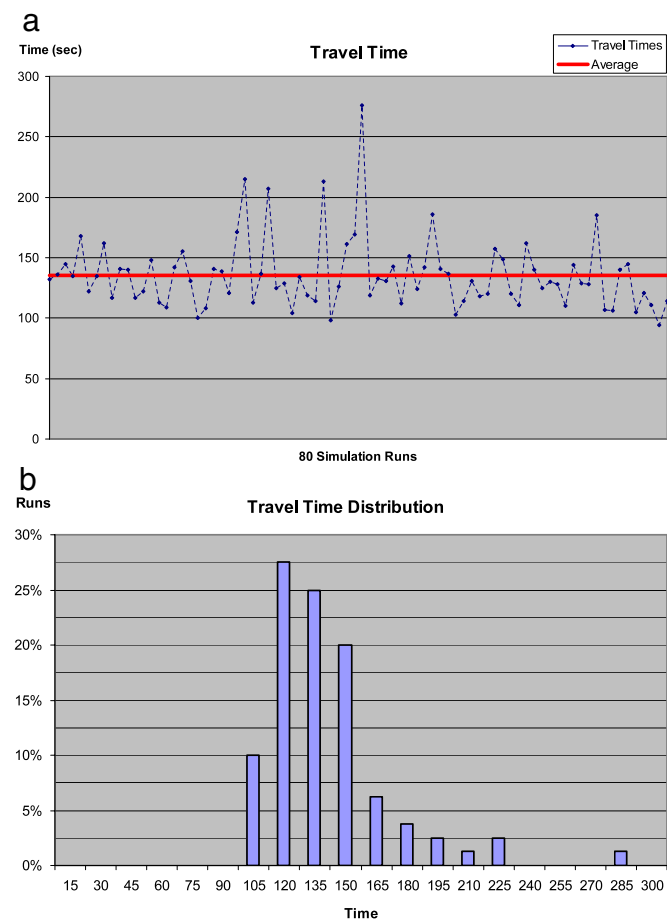
Fig. 11. (a) Travel time for each simulation run (bullets) and their average (solid line) and (b) travel-time distribution for the simulation runs.
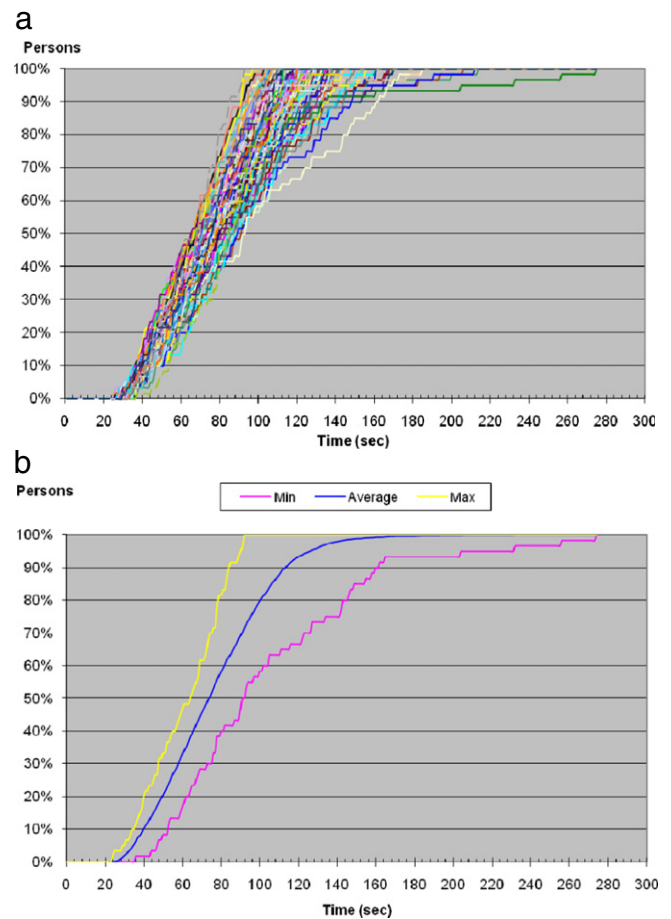
Fig. 12. (a) Cumulative arrival time at Muster Station for each simulation run and (b) minimum, average and maximum of the cumulative arrival time at Muster Station.

a

b

Fig. 13. Maximum and average passenger-density distributions for positions: (a) DS1 and (b) DS2.

a

b

Fig. 14. (a) Cumulative arrival time at Muster Station for each simulation run and (b) minimum, average and maximum of the cumulative arrival time at Muster Station.
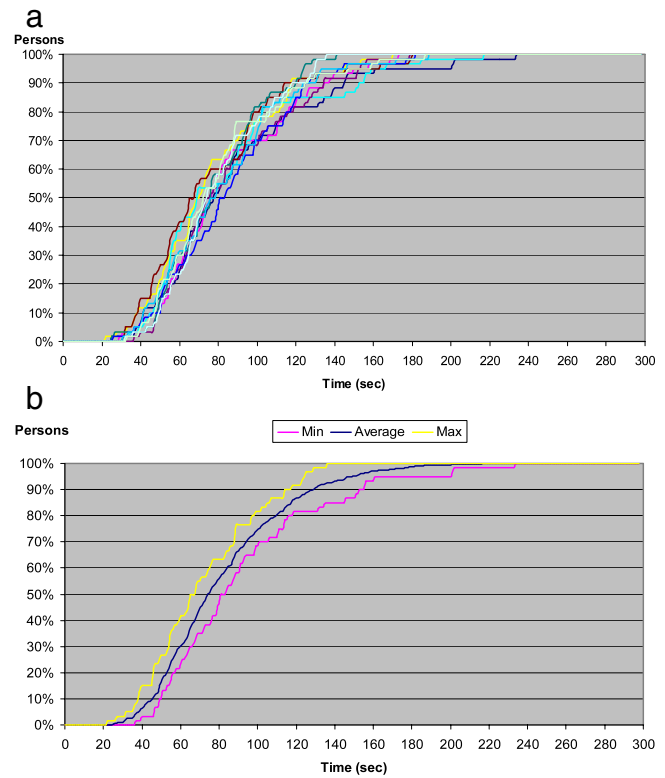

Fig. 15. Snapshot from VELOS rendering area focusing on the stairway under examination in Case 4.3.
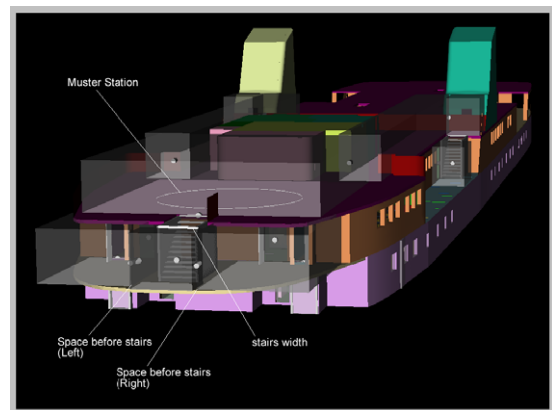
VELOS can be used to assess various aspects of ship performance, as, e.g., evacuation, ergonomics, comfortability, its evacuation module is mainly described and analyzed here. This work is in line with IMO Interim Guidelines for Evacuation Analysis of Passenger Ships and aims to develop an integrated environment for the rational analysis and assessment of real emergency conditions, removing in this way restrictive assumptions and omissions of IMO which lead to the need of safety factors. VELOS enhanced capabilities include:

- Dynamic derivation of the escape routes by the agents, using the provided path-planning functionality. In IMO method, the escape routes are fixed.
- Possible unavailability of escape arrangements due to fire or flooding.
- Influence of fire products (smoke/heat/toxic gases) to agents behavior.
- *Active evacuation process* comprising crew assistance and group behavior via behavioral modeling and user participation through avatar mechanism.
- Influence of ship motions and/or constant inclinations to the evacuation process through the Inclination behavior.

VELOS was demonstrated herein by performing evacuation analysis for a ro–ro passenger ship in intact and damaged condition employing both the simplified and VELOS advanced methods. The damaged-condition test demonstrates VELOS enhancement with the Inclination steering behavior. The obtained results are qualitatively as expected (i.e., longer evacuation time for the damaged

condition). Finally, in the third test case, we demonstrate VELOS capabilities as a design tool for evacuation.

Regarding future work, we consider that further systematic testing and ensuing development of VELOS functionalities in realistic conditions — including large cruisers and ro–ro passenger ships (>2000 pax) — is required for establishing VELOS as an evacuation analysis software tool. Furthermore, comparison with reliable experimental data would be obviously beneficial, although such results are currently unavailable and generally hard to produce.

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