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SIMULATION OF PASSENGERS MOVEMENT ON SHIP EMERGENCIES. TOOLS FOR IMO REGULATIONS FULFILMENT

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ABSTRACT

The main objective of this paper is to present the conceptual design, models and user oriented software tools developed to apply the IMO passengers evacuation rules in an automatic way. A summary of the main ship evacuation problems, underlining the differences between land and ship emergency situation are presented. Also we present the related IMO regulations with an historic and present rules review. We show the different numerical model types used for the study of pedestrian movement and its evolution towards cellular agents models. Also we present an historic overview of the work made in this area by our Spanish research group. Finally the results inside the SIFBUP research project are presented. Its main aim is the analysis and simulation of the passengers flow aboard ships, specially focused in the resolution of problems related with ship evacuation in emergency situations.

Key Words: Ship evacuation, pedestrian movement, cellular agents model.

INTRODUCTION. THE SHIP EVACUATION PROBLEM.

The well-known disasters of the Herald of Free Enterprise, Scandinavian Star and the Estonia have set a new regulation about passengers safety and crew training of passengers ships that include ship evacuation and evacuation aids.

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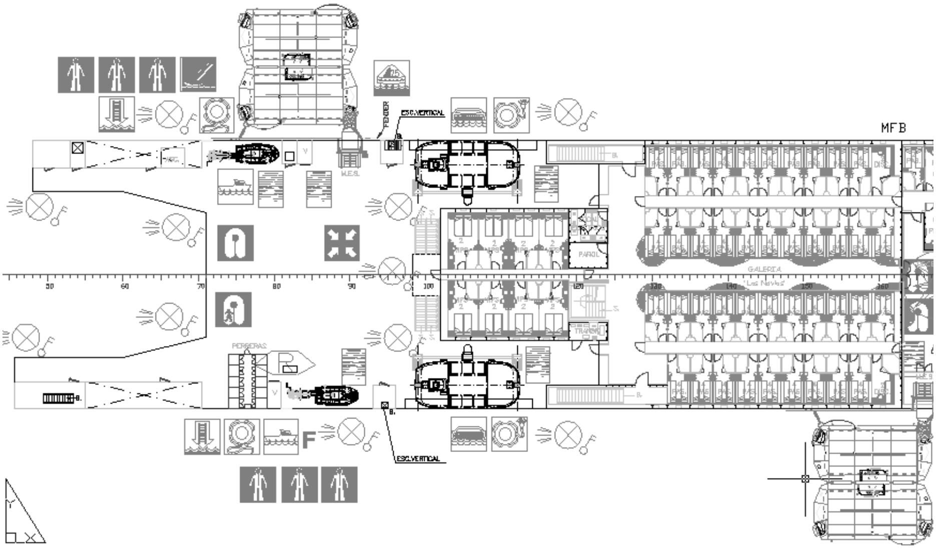

Figure 1. Partial view of ship evacuation facilities

In all transport and public building it is compulsory to have a scheduled evacuation plan and during an emergency situation all people must follow it. From the post-catastrophic analysis of significant events, the experts underline the following people behaviour:

— Most of people do not start walking the emergency alarm sounds. There is an important delay to react to the alarm indication, known as "awareness time".
— People usually follow a known route better than follow the emergency exit symbols.
— In general, people move with a strong influence of their relatives behaviour.
— Evacuation symbols are not followed, especially if they are text ones.
— Physical and psychological constraints are very important, with significant variation between different people types.
— People can go through a smoky area of reduced visibility, especially if they know well the place or if someone acting as a leader guides them.
— In crowded situations, it is not common the generation of a panic situation.

But also there are big differences between land emergency situations and ship evacuation (Lopez, 2002). The environment and the human behaviour are quite different due to:

— Distribution and evacuation aids that are unknown for the normal passenger.
— Different crisis origin.
— Movements are difficult in a non-horizontal and unsteady platform.

— The ship is isolated and frequently in a "rough sea".
— People (passengers and crew) with multilingual and multicultural origin.
— Different ship operation situations.

Due to the mentioned reasons, passenger ship evacuation is a complex process (figure 1). According to IMO regulations (MSC, 2002) it must be scheduled in mustering and abandon phases (M&A). The first is an uncontrolled movement of people from the initial places to assembly stations. In the second stage the passengers have to be guided (controlled) by crewmembers that develop a supervised plan avoiding unnecessary crowds and queues.

Evacuation may happen at any time while sailing. So, facilities for it must be always ready. The crew must be trained with frequent aboard exercises. They will know the evacuation ways and their duties at these situations. Maintenance of the evacuation ways and lifesaving systems is also an important matter.

According to IMO, the main part of the Ship Evacuation Plan (SEP) is: "an operating guide, either printed or in computer format, where missions and duties of the crew, basic operations sequence and operating criteria (with examples, if possible) are indicated". The main interfaces of the SEP with passengers' evacuation are the information sings in the escaping routes and the instructions in the case of ship evacuation. A good SEP must:

— Be easily managed; with a clear abandon group definition and their travel schedule (without crossing or overlapping between groups).
— Calculate, with a suitable reliability level, the arrival time to the mustering stations for the different passengers groups.
— Calculate and minimise the time between the ship abandon command and the moment that the last person abandons the ship.

During emergency stage, the situation must be managed according to the SEP through appropriate decisions and commands according the two phases of the M&A process. From the start of the emergency signal and during the mustering phase there will be few control (formally there will be uncontrolled passenger movement). Passengers go to the assembly stations following the main or the secondary evacuation plan and signals.

Then, the crew verify passenger's number and their lifejackets use. When the Master give the "ship abandon" order, the crew lead the passengers towards the embarkation points (evacuation stations) in "controlled groups" through the ship evacuation routes, moving at a near-optimal speed and flow. For this controlled passenger' flow, there are two different options: one member of the crew acts as a "leader" for a group of passengers, or different crewmembers are placed in critical points of the evacuation route in order to guide the passengers and regulate their flow.

As a consequence of the mentioned above, the need of specific models and tools for the ship evacuation analysis is clear.

IMO REGULATIONS

IMO (International Maritime Organisation) from a long time has published an extensive normative about ship evacuation, meanly in SOLAS regulation (IMO, 1973), mainly defining the safety boats and rafts number and characteristics. Until the last century end, the main regulation about inside ship design related with evacuation was the Amendment 757 that regulates the stair wide. This situation has changed by mean of the work of the IMO MSC (Maritime Safety Committee).

In 1999 the MSC published the Circular 909 tilted "Interim guidelines for a simplified evacuation analysis of ro-ro passenger ships" (MSC, 1999) that was the first attempt to have a whole analysis about the passenger movement inside ship during emergency situation. Other IMO regulations have been publishes in order to improve the evacuation process on different passenger ships (Ro-pax, HSC, large passenger ships, etc.).

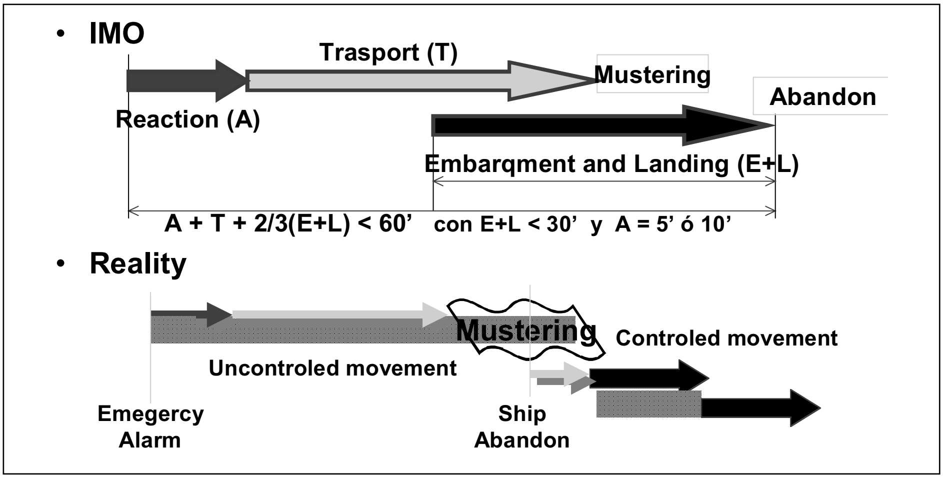

Figure 2. Comparison between IMO SEP and real situations.

Finally the MSC has published in June 2002 a document (MS-c1033) titled "Interim guidelines for evacuation analysis for new and existing passenger ships" (MSC, 2002), that includes two analysis methods. This guide mentions that further investigations and developments are necessary. It offers the possibility of using two different methods:

— A simplified evacuation analysis.

— An advanced evacuation analysis.

The Committee, as far as both methods need to be extensively validated, agreed that the Guidelines would have an interim nature and that the evacuation analysis methods should be reviewed in the future with the light of the results of experience using the present Guidelines, ongoing research and development aiming at applying only the advanced evacuation method and, when available, analyses of actual events utilizing it.

The **simplified analysis** is based in a macro-model adapted from the buildings evacuation method (Perez, 2003). For the calculation of the evacuation time, the following components are considered:

— The awareness time (A) is the one that people need to react to an emergency situation.
— The travel time (T) is defined as the time it takes people to move, to the assembly stations and the embarkation stations. For its calculations, a hydraulic macro-model is used, based on a speed-density function modelled with data of table 1.
— The embarkation and launching time (E+L) is the sum of the time required to provide ship abandonment.

The evacuation process, as illustrated in figure 2, should be complied with:

— Calculated total evacuation time: $A + T + 2/3\ (E + L) \leq n\ E + L \leq 30'$ For Ro-Ro passenger ships, n = 60. For passenger ships other than Ro-Ro passenger ships, n = 60 if the ship has no more than 3 main vertical zones; and 80, if the ship has more than 3 main vertical zones.

With the **advanced evacuation analysis** each occupant is studied as an individual that has a detailed representation of the layout of a ship and simulates the interaction between people and the ship environment.

Type of facility	Initial density D (p/m2)	Initial specific flow Fs (p/(ms))	Initial speed of persons S (m/s)
Corridors	0	0	1.2
	0.5	0.65	1.2
	1.9	1.3	0.67
	3.2	0.65	0.20
	≥3.5	0.32	0.10

Table 1. Values of initial specific flow and initial speed as a function of density.

This method of estimating the evacuation time is based on several idealized benchmark scenarios and the following assumptions are considered:

— Passengers and crew are represented as unique individuals with specified individual abilities and different response times.
— Passengers and crew will evacuate via the main escape routes.
— Passenger load and initial distribution is based on chapter 13 of the FSS Code.
— Full availability of escape routes is considered unless otherwise is stated.

At least, four scenarios should be considered for the analysis. Two scenarios, namely night (case 1) and day (case 2) and, two further scenarios (case 3 and case 4) based on reduced escape route availability are considered for the day and night case.

The Guide permits a big freedom in the model choice with the following limits:

— Each person is represented in the model individually.
— The abilities of each person are determined by a set of parameters, some of which are probabilistic as show in table 2.
— The movement of each person is recorded.
— The parameters should vary among the individuals of the population.
— The basic rules for personal decisions and movements are the same for everyone, described by a universal algorithm.
— The time difference between the actions of any two persons in the simulation should be not more than one second of simulated time, e.g. all persons proceed with their action in one second (a parallel update is necessary).

Also the Guide explain a validation procedure with 11 test designed to check that pax moves:

— With speed, flow and reaction times corrects.
— In a logical mode against obstacles and counter-flow.
— With whole results in complex scenarios consistent whit changes in the flow parameters.

Population groups - passengers	Walking speed on flat terrain (e.g. corridors)		
	Minimum (m/s)	Mean (m/s)	Maximum (m/s)
Females younger than 30 years	0.93	1.24	1.55
Females 30-50 years old	0.71	0.95	1.19
Females older than 50 years	0.56	0.75	0.94
Females older than 50, mobility impaired (1)	0.43	0.57	0.71
Females older than 50, mobility impaired (2)	0.37	0.49	0.61
Males younger than 30 years	1.11	1.48	1.85
Males 30-50 years old	0.97	1.3	1.62
Males older than 50 years	0.84	1.12	1.4
Males older than 50, mobility impaired (1)	0.64	0.85	1.06
Males older than 50, mobility impaired (2)	0.55	0.73	0.91
Population groups - crew	**Walking speed on flat terrain (e.g. corridors)**		
	Minimum (m/s)	**Mean (m/s)**	**Maximum (m/s)**
Crew females	0.93	1.24	1.55
Crew males	1.11	1.48	1.85

Table 2. Example of population data.

The travel time, both that predicted by models and as measured in reality, is a random quantity due to the probabilistic nature of the evacuation process. In total, a minimum of 50 different simulations should be carried out for each of the four-benchmark cases. A safety margin is added to account for the assumptions. It is 600 s for cases 1 and 2 and 200 s for cases 3 and 4

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— Details of the calculations.
— The total evacuation time.
— The identified congestion points.

PEDESTRIAN MOVEMENT MODELS

If we study the different approaches to pedestrian movement analysis, that is the base for aboard evacuation study, we can classify the used models in tree groups: macro-models, micro-models and meso-models.

Macro-models consider the behaviour of people movement analysing the global response of a group that occupies a local or sector. The main parameters are speed, maximum flow and passengers' density. From land evacuation studies, different functions have been proposed for the curve speed vs. density (figure 3). In optimal path analysis it is normal to consider constant speed and maximum flow.

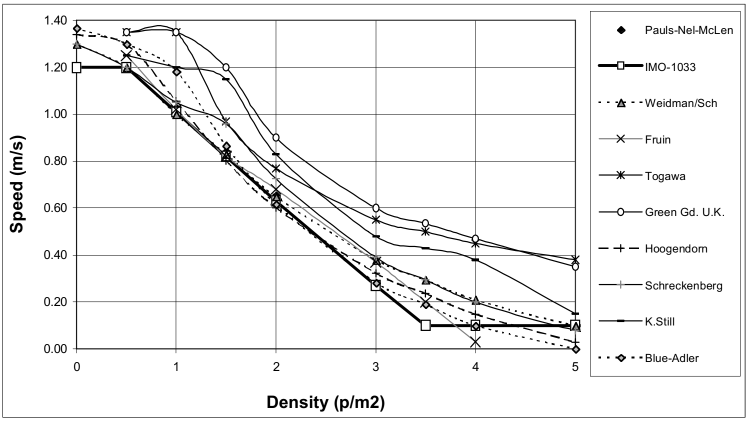

Figure 3. Speed vs. pax density.

In any case, the most important simplification is the modelling of people as a compressible fluid, with a maximum flow and density. Any situation that tries to overpass it, produces a "catastrophic" response (queue formation), This methodology is known as "hydraulic model".

Micro-model approach presents the movement of every person. There are three main approaches: linear, corpuscular and the cellular ones (Perez, 2001). At the moment the last one is the most popular on technical developments (Lopez, 2003). It is based in the division of the available space for motion in squared cells that can be occupied (or not) by a person.

The movement of every person is influenced by its objectives (direction, attraction, etc.) and by the occupation of the near cells (people, walls,). It is a discrete model (in space and time) well adapted for programming with "agent modelling" techniques. The Meso-model makes a mixture of previous models (Letizia, 2000), (Lopez, 2002). Generally it uses the macro for calculus and the micro for presentation.

One important modelling aspect is the variability of human behaviour. Data of figure 3 are mean values, but people speed can be a function of: age, gender, health, platform stability, etc. (Brumley, 200). Due to this reason, input data for the micro-models must be heuristic and tools based in it must use Monte-Carlo simulation methodology or other similar ones to obtain reliable statistical results.

In this moment the most advanced pedestrian movement simulation tools are based on cellular models. In it the space is divided is squared cells, and passengers are studied individually like. One person thereby occupies one cell and two different passengers cannot occupy the same cell. Other cells contain different information, depending on the way it influences the person standing on it. If it is not accessible, it represents an obstacle like a wall or furniture.

The individual behaviour of every passenger when going from cell to cell is studied by mean of an "agent model". Passenger's speed is influenced by passengers' density around, and by the number of cells in the advance direction that the person can move. One passenger cannot jump others to move forward them, and must go through left or right, if possible. If not, he must wait or move laterally in some cases.

SESAMO AND SIFBUP MODELS AND TOOLS

Since long time ago, Izar shipyards and the ETSIN R&D Group on Aboard Human Factors have a close collaboration in the study of ship evacuation problems. The first attempt start in 1997 with the B-09 Project, developed under the Astilleros Españoles (today integrated in Izar) direction. Its aim was to develop a new type of ro-pax ship, including the developing of tools for its evacuation analysis.

In this time there was no definitive method for studying the evacuation of a ship, so, the ETSIN evacuation research team developed a detailed study on advantages and disadvantages of different methods and their usage in practice. Based on this work some methods and tools have been developed for qualitative and quantitative analysis for ship evacuation. The acronym of these methods is SESAMO (Ship Evacuation Simulation and Analysis, Madrid Original). Their common model is a network inside the general arrangement for the study of the passengers flows follow-

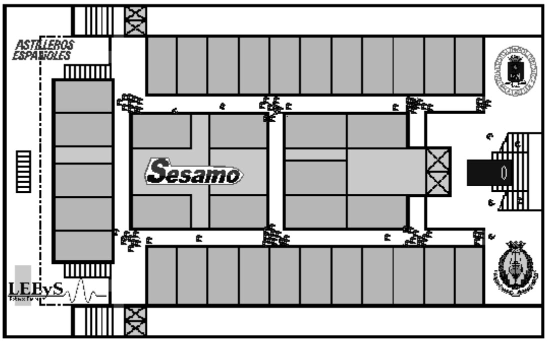

Figure 4. Graphical output of Sesamo-S program

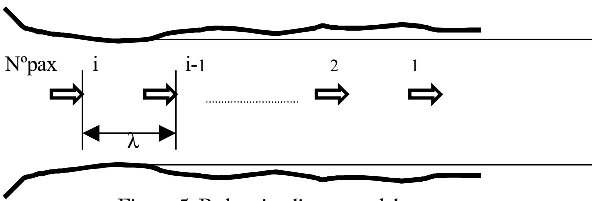

Figure 5. Pedestrian linear model

ing the hydraulic methodology with macro- and meso-models use. There are different versions with different in complexity (Lopez, 1999):

— P (Preliminary) A manual method that allows to check the evacuation plan and its devices in a few hours and see the critic points of the arrangement.
— M (Manual) The agreement with the MSCc909 normative of the evacuation plan is checked and specially the total time of evacuation. Excel ® support is used for the calculations.
— T (Temporal) Like M bu with a specific treatment of the beginning and disappearing of queues.
— S (Simulation) Based on useful tools for the study of the evacuation plan, evacuation routes and salvage devices. Arena support is used for the simulation, as show in figure 4.

When the B-09 was finishes the ETSIN R&D group study the feasibility of a micro-model based in the representation of individual passenger movement in corridors (figure 5). The model core was that the speed of a pax was function of the separation (l) with the previous one (Perez, 2001). The developing of MSC circular 10033 shows us that we must move toward cellular models.

Based in this previous experience, under the support of the Spanish R&D Program for the Shipyard Industry, sponsored by the Ministry of Science and Technology and controlled by the "Gerencia del Sector Naval", we started in 2002 the Sifbup project (DINN-17) with a team composed by:

— Izar, the Spanish main group of shipyards, as main partner with expert knowledge in ship design.
— The ETSIN as scientific partner and responsible of the development of the software tools.
— Trasmediterranea, the main Spanish company of passenger ships, with direct experience on passenger ship operation.

— Next Limit Company, experts on 3D simulation. Incorporated in the middle of the project life.

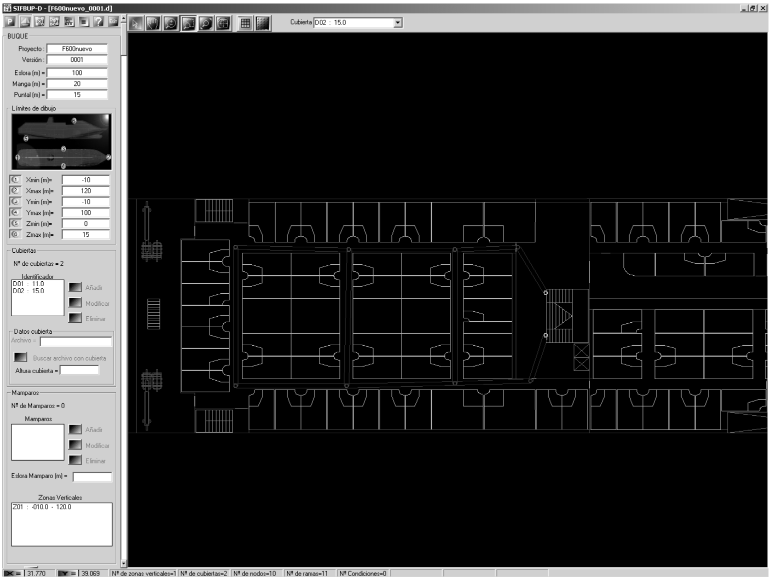

Figure 6. Sifbup-D user Interface.

The main project objective is to develop a family of tools designed to aid the study of aboard people and vehicles flow. We have developed different tools oriented to the various necessities along the ship' life, such us:

— The Sifbup-D, for the evacuation study in the first phases of the ship project.
— The Sifbup-S, a 2D simulation of people movement in normal aboard operation and in emergency situations.
— The Sifbup-S3D, to see the people movement in a "virtual reality" environment.
— The Sifbup-V, to analyse the load and unload operations of trucks, cars and other vehicles inside ferries and other Ro-Ro ships.

The Sifbup-D has been designed to fulfil with the MSC-c1033 simplified evacuation analysis with a design (figure 6) specially oriented to de preliminary ship design phase. It is based in a macro-model that could be of easy use and have a quick response. It uses an initial model of the evacuation network with nodes (gates, cross-points, etc.) and branches (corridors, stairs, etc.), like is showed in figure 7.

The macro-model computes the passenger evolution calculating the initial and final passing time of every passengers group through all the nodes that the group follows. It also includes the checking of possible interaction between groups in every node and the detection of queues.

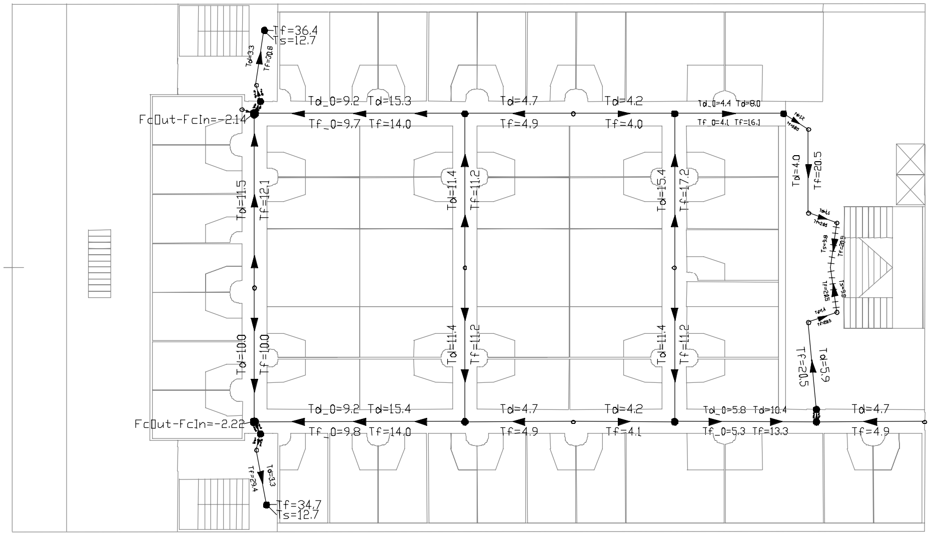

Figure 7 Sifbup-D Evacuation draw

THE SIFBUP-S MODEL

For the design of the Sifbup-S model we need to adapt the cellular model for complex spaces. The general arrangement of the ship or a part of it, with cabins, corridors and public spaces is imported (via a .dxf file normally) and floor is divided in squared cells of 0.4 by 0.4 meters (figure 8, left). This is a standard value in evacuation studies (Koning, 2001) that derives from the maximum density in crows when the movement reaches a stop.

This discreetization and the cell size could be an important error source. The main argument against the use of cells is the exclusion of small variations in the width of corridors or doors. In our design this problem is overcome with a coefficient that affects the speed and it is a function of the corridor or door with where the passenger is moving.

The next important design concept is that the ship and evacuation modelling is divided in these stages: Strategic, tactical and operative levels.

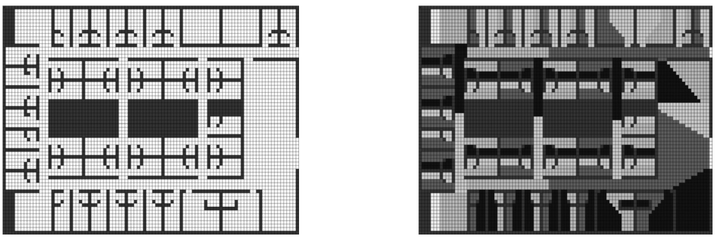

Figure 8. Discreetization in cells and tactical level.

The strategic level

In this stage we define the scenario layout and solve the problem concerning with orientation of a person is the global route choice. How a person evades obstacles and other passengers is considered in the operative level as is described forward, but the way that a person chooses where to go and to get there is the decisive problem. In the case of evacuation, this is called the evacuation plan that can be the main evacuation plan or secondary evacuation plan if the main is not possible because of fire or flooding for example.

Our cellular model can works with the information generated by the Sifbup-D, with branches and nodes in specific points. In this strategic level, decisions about the destiny points of the passengers (mustering and embarkment stations) are made. So, this strategic level is quite related with macro-models.

The tactical level

The main objective of this stage is to solve the direction in which passengers have to move in order to reach their goal (figure 8, right). So, a person knows where to move in the next time step and these motions will lead the final goal (mustering or embarkation stations). Crewmembers and passengers could have different routes towards the mentioned stations according their duty schedule at emergency, and sometimes, practically ever, there are encountered flows between crew and passengers. That is the reason because the model must solve encountered flows as it will be seen in the point IMO requirements, and every cell can have stored more than one route.

In our approach route information in given through potentials. This means that only goal cells have to be marked, and the potential will automatically spreads the directions from one accessible cell to the following and by this throughout the whole structure. When passengers reach the mustering stations, they wait in their cells until they can go to the different embarkation stations, as long as the lifeboat or other devices are being prepared.

Environmental conditions could be considered in this tactical level. If the ship is heeled port board during evacuation, the directions of the cells can be changed, “pushing” or changing the tendency of motion port board. Rolling motion can be also considered, by doing a periodical change of the tactical level (meanly in the speed effect) with the modal period of the Sea State where evacuation occurs. The effect of the environment can also affect speed in the operative level.

The operative level

Form the model work; this is the most important level. Every passenger is represented by an “agent” with interact with two cell matrixes at every moment: A sight matrix and a motion matrix. These have studied dimensions in order to have an optimal point between precision and computer time. In figure 9 on show different situations for a pedestrian reserved cells are presented as arcs and selected path for advance with an arrow.

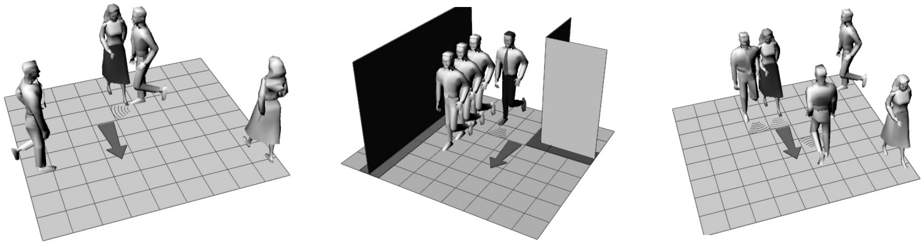

Figure 9. Examples of the operative level.

Passengers' density is calculated in a cell matrix that surrounds the passengers (sight matrix). With this passenger's density, speed can be obtained through an expression based in experimental results. According table 1 we use the following:

$$
\begin{aligned}
S &= S0 \cdot 1 \; ; D \quad 0.5 \text{ pax/m2} \quad [1] \\
S &= S0 \cdot (1.153 - 0.306 \cdot D); 0.5 < D \quad 3.5 \text{ pax/m2} \\
S &= S0 \cdot 0.082; 3.5 < D \text{ pax/m2}
\end{aligned}
\qquad (1)
$$

Where S0 is a probabilistic function of the passenger type (crew, age, gender,) and MSC-c1033 Annex 2 also provides the values and D is the passengers density measured in the sight matrix. As far as the advance is a multiple of the cells length, sometimes a passenger will advance more than the exact value assigned by the speed function, and other times less. This lack or excess in the advance distance should be taken into account to correct the advance in the next time steep.

But a passenger can advance only the number of free cells in the direction of motion which is assigned in the tactical level, so this calculation is made in the motion matrix, and the lower of these two values (cells assigned by the speed function and free cells) is the number of cells that a passenger advances in this time step. So, a passenger can choose advance through the column or row of cells (path) of the centre, left, or right, chosen with an optimum path algorithm.

Every passenger reserves also one cell just in front of her for the next time step (arcs in figure 9), and this cell cannot be occupied or crossed by other passenger. This is a polite behaviour, trying not to disturb the advance of the rest of the passengers crossing their way, and in case of encountered flows, trying not to be face to face of other passenger.

THE SIFBUP-S APPLICATION

Once we developed the cellular model for the movement of persons in complex geometry environments, we made its implementation in a computer application (the Sifbup-S), using Visual-Basic programming language

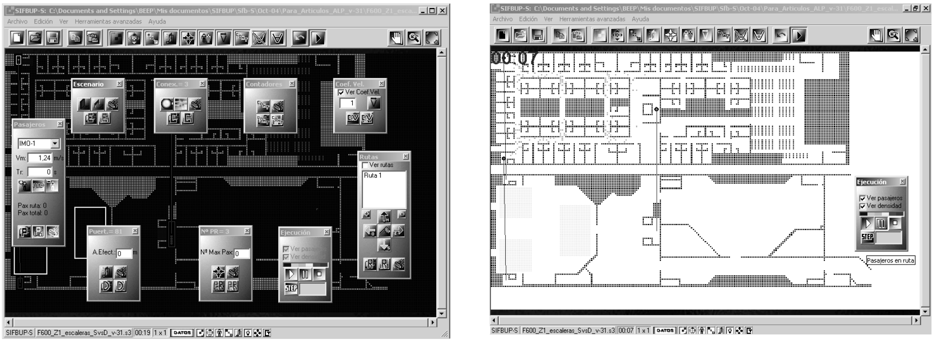

Figure 10. Sifbup-S edition an execution interfaces.

Our objective was to develop a flexible application, modular, integrated and oriented to the user (Lopez, 2003). The participation in the project of a shipyard, a ship owner and a company leader in visualization software were fundamental for its practical aspects. As a specification summary, the Sifbup-S has been designed to solve the following objectives:

— It fulfils with the advanced method of the MSC-c1033.
— Its concept design is opened, allowing the simulation of the movement of persons in 2D in complex stages.
— For the definition of the case and its analysis, it uses a modular structure with several data files that allow the use of previous work to modify or expand the present project.
— This structure allows to be integrated with other applications, such us CAD ones importing design in .dxf format, and the Sifbup-D and Sifbup-S3D.
— The user can start with a general analysis of the ship zones, using quick input data and then the user can improve the model, working with greater precision (doors, speed coefficients, etc.) at the critical zones.
— The 2D simulation allows a global and detailed vision of the evolution of a situation.
— The graphic interface design is highly ergonomic with Windows structure and an extensive mouse use.

In figure 10 we see the application general aspect in the edition and calculation modes.

The edition process can also be accomplished in manual form, if we have not any previous data files, or in an automated way if we have previous studies from other applications. In the first case it is compulsory to provide the following data:

— Layout representation.
— Routes definition (field of directions)
— Pax placement in theirs start points
— Connections (staircases) between decks or floors.

When the project definition is finished, we can start the simulation. We will see in the screen all pax movements (figure 11). In order to make easy this graphic analysis the application has several usual post-process facilities (Scroll and zoom; Stop (pause) and step-by-step execution; Image capturing; etc...) and each pax has a triple symbol tag:

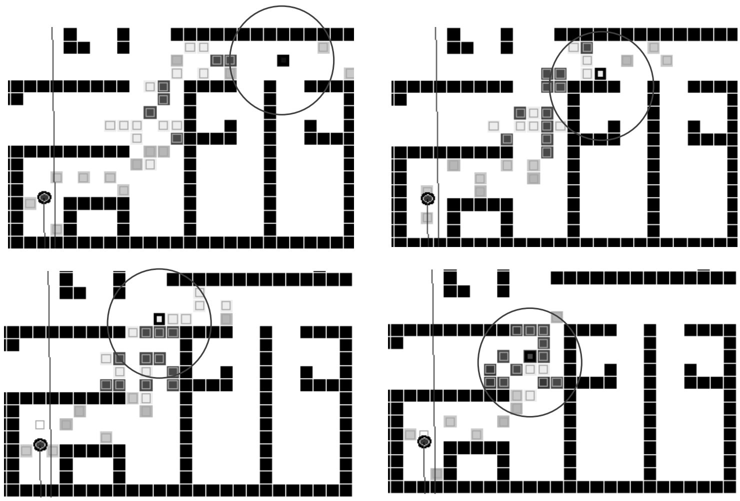

Figure 11. Advance images of a tagged pax.

— The symbol shape: represents the pax type, which is related to his maximum speed.
— The symbol colour: shows the pax origin (route).
—The cell background: informs about the density around a cell.

When calculation phase is finished, a special mark appears on all the cells which density have overcomes a threshold limit during a significant period of time. By this way is easy to identify the crowded zones that will affect seriously to the evacuation process.

By default the calculation mode works with a deterministic method. This helps the post-process and initial analysis. According to the advanced methodology indicated by the regulation MSC-c1033, the application has also a random analysis mode. This randomises automatically the properties of each pax and allows a statistic analysis of the total time of the evacuation, with multiple speed and awareness time distribution for a given study.

The program also exports the following information:

— Evolution of the pax number along time in the points were counters are placed.
— Multiple "photos" of the process.
— Video image of all the evacuation process (using external tools).
— Statistic results.
— Final pax position.
— Path of every single pax during the simulation. Starting with this data file we can work with the application Sifbup-3D to generate a simulation in 3D, as shown in figure 12 with the scene visualization controlled by the user (virtual reality).

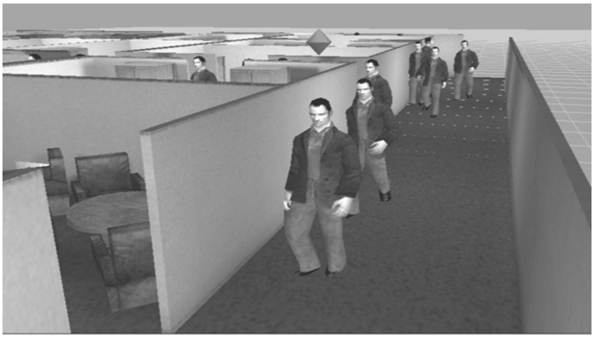

Figure 12. 3D evacuation simulation.

CONCLUSIONS

The evolution on maritime regulations on people onboard behaviour during emergency situation has been presented, showing the trend to the use of simulation tools, Also, the necessity of special models to study the movement of people on complex and size limited scenarios has been showed, with the special requirements to use them on ship emergency evacuation simulations.

The accomplishment of the existing regulation has to be implemented with a family of models and modular tools in order to make easy the designers work. For the first steps a macro-model will be the optimal solution if it can be connected with more advanced model

Our approach to solve the simulation approach, was based on an improved cellular agent model; it is a good solution, not only on the theoretical face, but also on their easiness to use it to develop a used oriented application for the pedestrian flow aboard simulation.

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