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SIMONE: A Dynamic Monitoring Simulator for the Evacuation of Navy Ships

Heitor Martinez-Grueira [1,†], **Rafael Asorey-Cacheda** [2,*,†], **Antonio-Javier Garcia-Sanchez** [2,†] and **Joan Garcia-Haro** [2,†]

[1] Decision Support Techniques Section of the Navy Staff, Spanish Navy, 28071 Madrid, Spain
[2] Department of Information and Communication Technologies, Universidad Politécnica de Cartagena, 30202 Cartagena, Spain
* Correspondence: rafael.asorey@upct.es; Tel.: +34-968-326-537
† These authors contributed equally to this work.

Abstract: In this paper, the automation of the evacuation process of a military ship is studied in real time. For this purpose, a scenario is reconfigured to produce a failure or damage. Then, an optimal network of alternative escape routes is computed. The resulting escape route map can be indicated by lighting the appropriate corridors on the ship. Through these corridors, the members of the embarked population and the entire process is monitored so that the crew can reach their lifeboats in the shortest possible time. To undertake this automated process, the dynamic ship evacuation monitoring system (SIMONE, from its acronym in Spanish: Sistema de Monitorización Dinámica de Evacuación de Buques) has been developed. This system integrates a communication gateway with the integrated platform control system (IPCS) and integrated lighting system that will be installed in new Spanish naval constructions.

Keywords: ship evacuation; monitoring simulator; time optimization

Citation: Martinez-Grueira, H.; Asorey-Cacheda, R.; Garcia-Sanchez, A.-J.; Garcia-Haro, J. SIMONE: A Dynamic Monitoring Simulator for the Evacuation of Navy Ships. *Appl. Sci.* **2022**, *12*, 11786. https://doi.org/10.3390/app122211786

Academic Editor: Christos Bouras

Received: 25 October 2022
Accepted: 17 November 2022
Published: 19 November 2022

1. Introduction

The correct design of ship evacuation plans can save many lives in emergencies, and several works in the literature focus on this area [1–3]. However, almost all of these evacuation plans are impractical in the case of military ships. The key difference this type of ship has is that its crew does not usually fit the profiles of people on other ships. In addition, the type of emergency situations can be very different due, among other things, to damage from military actions or war [4]. Thus, the main contribution of this article is the presentation of a simulator based on graphs that can minimize evacuation times in real time from anywhere on the ship for any member of the crew. This is why the combination of this tool with the ship's control systems and the positioning of its crew will result in a great improvement in survival rates in the event of a breakdown.

Although it is now a critical issue on any ship, well into the late 20th century, passenger and crew safety was not a relevant issue from a technical or legislative point of view [5]. However, the safety of crews on military ships requires different treatment because they are highly qualified personnel whose activities under critical situations entail enormous risk. Thus, the navy has remained at the forefront of technical and technological maritime security development.

The regulatory homogenization project involving the member navies of the North Atlantic Treaty Organization (NATO) began with the first version of the Naval Ship Code (NSC) [6] as a way to standardize the different regulations among the allied armed forces. Chapter VII of the NSC concerning escape, evacuation and rescue (EER) adopts and homogenizes security regulations among NATO navies. Once the Spanish Navy learned of this initiative, it commissioned its military operational research office (Gabinete de Investigación Militar Operativa, or GIMO) to study EER [7]. Sufficient knowledge to evaluate the safety standards of their ships was gathered to comply with the new NSC.

From its first version, the NSC has dealt extensively with EER, albeit generically. Chapter VII of the NSC frequently refers to standards and data from civil regulations adopted by the International Maritime Organization (IMO). These regulations contribute little to the naval environment. One of the first obstacles was the impossibility of applying the population distribution adopted by the NSC to a warship because it corresponds to the distribution assumed by the IMO regulations for the passenger and crew of a civil vessel [8]. This distribution provides some sex, age, and disability ratios, and it also distinguishes between passengers and crew. These are implausible on a naval ship.

Based on initial knowledge, the GIMO proposed a minimalist approach involving a preliminary stage to determine the distribution of the embarked military population and then consolidating a base of information to undertake future studies [9]. This approach was transcendental because applying new techniques and technologies to data acquisition and analysis of data better reflected the population distribution of a navy ship and identified its main anthropometric characteristics, most relevant professional attributes, and predominant behavioral skills.

With this knowledge, a statistical design of experiments (SDE) was proposed to identify the intervening factors (body mass index, age, and seniority) [10], and delimit the displacement of the embarked population on a military ship [11]. In this way, the regression functions that quantify and model the displacement of the members of the crew can be calculated. Due to its size, this represents the most relevant contingent of an amphibious ship [12].

These first studies were successful, and they provided essential knowledge to enable the validation of the evacuation protocols implemented by the Spanish navy on its ships. These protocols are more complete and restrictive than those included in the EER of the updated NSC [13].

This initial research led the way to defining and formulating more specific and ambitious investigations, including “The evacuation of the warship,” a PhD dissertation [14]. It provided a distribution model for the embarked population and a methodology supported by a linear programming problem (LP). This methodology designed the optimal escape routes on any warship. Based on these routes, lifeboats could be optimally assigned to the different members of the crew, and evacuation could take place in the shortest possible time.

After the enactment of the current Spanish Personnel Law [15], the progressive aging of crews was expected. This has been confirmed by the diagrams shown in Figure 1, in which we can see the median of age distribution for officers. According to the DEE, the age factor acts as a variable restricting the displacement model of the embarked population. Aging will inevitably affect displacement capacity.

Having defined the simulation scenario based on the general layout of the study ship and its network of evacuation routes based on the proposed LP problem, and given the characteristic data of the embarked population and its displacement model, the preestablished evacuation plan for the type of ship under study will be validated [16].

The main contributions of this article are summarized below. The optimization problem for the evacuation of ships is analytically described. An algorithm is proposed to solve this optimization problem. Finally, SIMONE, which implements this algorithm, is presented, and the features it offers are compared with the reference software for ship evacuation, MaritimeEXODUS. These results show that SIMONE offers better performance than MaritimeEXODUS. In fact, MaritimeEXODUS is unable to solve the most complex cases in which a ship has suffered significant damage.

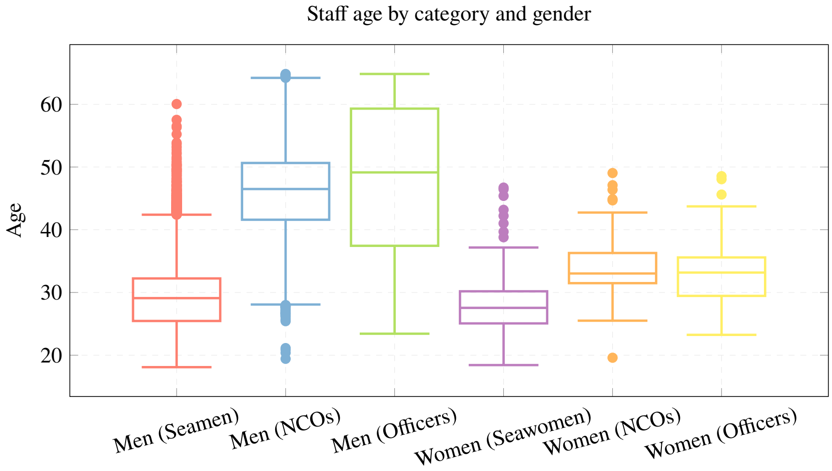

Figure 1. Spanish navy staff age by category and gender in 2007 [14].

The rest of this paper is organized as follows. Section 2 provides a background on the particularities of naval ship evacuation and its optimization. Section 3 formulates the optimization problem. Section 4 describes how optimization is implemented by means of a recursive algorithm. Section 5 discusses the results for different scenarios and levels of ship damage. Finally, Section 6 concludes the paper.

2. Background

Because it is not feasible to undertake a real simulation under a series of foreseen and unforeseen circumstances, the only plausible way to address the validation of a navy ship evacuation plan or protocol is to use a nondeterministic simulator.

To quantify and validate the characteristics of the scenario we configured, the IMO has progressively adopted microscopic models in its standard to emulate the evacuation process on board a ship. In fact, the MaritimeEXODUS application [17] version 4.0 (manufactured by the University of Greenwich, London, UK) is referenced by the IMO as a validation tool in its MSC/Circ.1238 [18] and, therefore, in the NSC [13].

The MaritimeEXODUS application has great capacity for configuring the general layout of a naval platform in real situations (breakdowns, heel, disabled spaces, etc.) as simulation scenarios, in addition to the intervening agents that emulate the embarked population. This simulator employs a network of nodes that like tiles, determine the transit or occupation options of a single agent at a specific time. Each agent then goes to a specific sink node that, in turn, emulates a lifeboat. The agents, characterized as instantiated objects and configured with attributes provided by the population distribution of a military ship, allow us to simulate the evacuation process of the population on board the ship.

The MaritimeEXODUS simulator implements an internal clock, which reevaluates and relocates the intervening agents in the corresponding adjacent tiles throughout the scenario every twelfth of a second until they finally reach the designated sink node (lifeboat). MaritimeEXODUS also defines the movement of an agent through routes previously established by the operator or by setting the criterion of the shortest path (distance) as a reference.

After running a sufficient number of simulations of the evacuation process and analyzing the results, we can confirm that the dimensions of the ship and the population on board do not influence the configuration capacity or power of the simulator, provided that the integrity of the network of predefined evacuation routes is not affected by unexpected failures. This approach, however, is not realistic, because it does not consider the characteristics of an emergency event. The order to abandon ship will be given by the command as a result of an emergency or breakdown, meaning that the physical integrity of the ship and the embarked population are at risk. Therefore, the network of escape routes will inevitably be affected.

The MaritimeEXODUS simulator is a powerful and versatile simulation tool that facilitates the configuration of a scenario and simulation of a process. The results can validate compliance with the precepts, provisions, and current regulations of a naval ship evacuation plan. However, this tool is not adequate to carry out the simulation of an unforeseen situation due to the excessive time needed to configure such a specific scenario.

As an alternative approach, the concept of dynamic evacuation, published in [19], is applied to model a dynamic scenario, emulating the general layout of a naval platform. This dynamic model admits partial restrictions on its structure to include those resulting from an unexpected breakdown or emergency.

To address the optimization problem, a succession of methods is implemented to emulate an optimal evacuation process on board a warship. This is accomplished through the interaction of a dynamic structure (dynamic graph) modeling the reference platform and several agents representing the embarked contingent.

Once the environment has been configured and the intervening agents have been monitored, a method supported by a graph vertex covering algorithm is implemented [20]. This method computes the minimum evacuation cost (time) estimated at each vertex—that is, the minimum cost attributed to an agent located at that vertex to reach its specific sink vertex on the graph. Then, based on the costs associated with each vertex of the graph already computed, a greedy algorithm is implemented [20] to identify the optimal route (shortest estimated time) of a specific vertex, or the branch on the graph that has the lowest cost between a vertex and a given sink. When the optimal route has been identified, an agent located at the vertex is relocated to its corresponding attached vertex. This method is implemented by using recursive programming [21] because it is more suitable for roaming through a dynamic structure scenario.

3. Statement and Formulation of the Problem

The development of an application (SIMONE) with the capacity to reconfigure an environment in the event of failure is proposed. This implies recalculating the network of alternate routes through which the embarked contingent will move. To do this, a powerful simulation engine undertakes real-time monitoring and optimal management of the crew to evacuate it in the reconfigured scenario in the shortest possible time.

To provide the SIMONE simulator with the aforementioned capabilities, it must be integrated into the IPCS (see Figure 2) through a communications gateway. This is a system that automatically evaluates, identifies, and quantifies the damage the incident causes to the general layout of the ship. Thus, to monitor the contingent of reference, we implement a network of RFID nodes. This is widely deployed and validated technology that was applied in the study undertaken by the GIMO. It allows us to monitor the position of the members of an embarked population as they move throughout the naval platform.

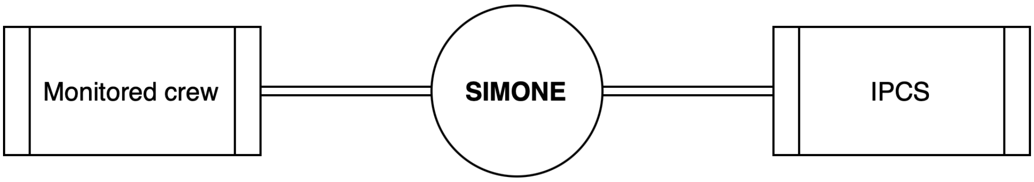

Figure 2. Data flow diagram (DFD, level 0). Functionality of the proposed system.

Following this functional model for the SIMONE simulator and the methodologies and techniques implemented [22], it is possible to develop and program the engines that emulate the supervening scenario and the optimal evacuation process to obtain the fastest possible evacuation.

The proposed model seeks to minimize the evacuation times of each member of the embarked contingent, thereby minimizing the total time used for evacuation. The magnitude or reference value of the process will be determined by the time taken by the last agent to leave the platform. Considering the premises, characteristics of the problem, and stated solution, its resolution is mathematically formulated as follows.

$n \in \mathbb{N}$ is the number of people making up the population on board a navy ship.

$P = \{p_1, p_2, \ldots, p_{m_1}\}$ is the set of different compartments/rooms into which we have divided the ship and that indicate the location of any member of the embarked population.

$B = \{b_1, b_2, \ldots, b_{m_2}\}$ is the set of available lifeboats on the ship.

$\tilde{p} = (\tilde{p}_1, \tilde{p}_2, \ldots, \tilde{p}_n)$, where $\tilde{p}_i \in P$, $i = 1, \ldots, n$, denotes the location of each arbitrary member i of the crew.

$\tilde{b} = (\tilde{b}_1, \tilde{b}_2, \ldots, \tilde{b}_n)$, where $\tilde{b}_i \in B$, $i = 1, \ldots, n$, denotes the assignment of a particular lifeboat to each member i of the embarked population.

For each $p \in P$ and for each $b \in B$, the following holds.

- $\phi^j(p, b)$ is a possible route (without loops), leading us from starting point p to boat b.
- $\Phi_{p,b} = \{\phi^j(p, b)\}_{j \in J_{p,b}}$ is the set of all possible routes (without loops) from starting point p to boat b.

Finally, we define

$$\Phi = \bigcup_{\substack{p \in P \\ b \in B}} \Phi_{p,b} \tag{1}$$

as the set of all possible paths (without loops) from any starting point to any destination boat.

Given an initial location $\tilde{p}$ and an assignment of boats b, the set of all available routes $\widetilde{\Omega}_{\tilde{p},\tilde{b}}$ for the embarked population is defined as

$$\widetilde{\Omega}_{\tilde{p},\tilde{b}} = \bigcup_{\substack{\phi_1(\tilde{p}_1,\tilde{b}_1) \in \Phi_{\tilde{p}_1,\tilde{b}_1} \\ \phi_2(\tilde{p}_2,\tilde{b}_2) \in \Phi_{\tilde{p}_2,\tilde{b}_2} \\ \cdots \\ \phi_n(\tilde{p}_n,\tilde{b}_n) \in \Phi_{\tilde{p}_n,\tilde{b}_n}}} \{\phi_1(\tilde{p}_1, \tilde{b}_1), \phi_2(\tilde{p}_2, \tilde{b}_2), \ldots, \phi_n(\tilde{p}_n, \tilde{b}_n)\}, \tag{2}$$

where $\phi_i(\tilde{p}_i, \tilde{b}_i) \in \Phi_{\tilde{p}_i,\tilde{b}_i}$. That is, each onboard member located at a certain location $\tilde{p}_i$ and with a lifeboat $\tilde{b}_i$ assigned obtains a possible route $\phi_i(\tilde{p}_i, \tilde{b}_i)$ to reach it. By construction, it is obvious that $\widetilde{\Omega}_{\tilde{p},\tilde{b}} \subseteq \Phi^n$.

$\tilde{p}$ is an initial location and an assignment of boats $\tilde{b}$. For each possible route $\tilde{\omega}_{\tilde{p},\tilde{b}} \in \widetilde{\Omega}_{\tilde{p},\tilde{b}}$, the function is

$$T : \widetilde{\Omega}_{\tilde{p},\tilde{b}} \to \mathbb{R}^n,\ T(\tilde{\omega}_{\tilde{p},\tilde{b}}) = (T_1, T_2, \ldots, T_n), \tag{3}$$

where $T_i(\tilde{\omega}_{\tilde{p},\tilde{b}})$ reports the time it takes for crew member i to get from his/her initial position to the lifeboat from the instant the abandon ship order is given.

Due to the dynamics of the problem under study, it should be emphasized that

$$T_i(\tilde{\omega}_{\tilde{p},\tilde{b}}) = T_i(\phi_1(\tilde{p}_1, \tilde{b}_1), \phi_2(\tilde{p}_2, \tilde{b}_2), \ldots, \phi_n(\tilde{p}_n, \tilde{b}_n)), \tag{4}$$

because this time depends not only on the route taken by crew member i but also the routes assigned to the rest of the embarked population because blockages may occur in different areas of the ship.

For an initial configuration $\tilde{p}$, $\tilde{b}$, and a route $\tilde{\omega}_{\tilde{p},\tilde{b}}$, the evacuation time is defined as the first instant that the entire embarked population is in the lifeboats; that is

$$t^{ev}(\tilde{\omega}_{\tilde{p},\tilde{b}}) = \max\Big\{T_i(\tilde{\omega}_{\tilde{p},\tilde{b}}), i = 1, \ldots, n\Big\}. \tag{5}$$

In general, the ship is in state k, where the location of the members is known $\tilde{p}^k = (\tilde{p}^k_1, \tilde{p}^k_2, \ldots, \tilde{p}^k_n)$. In addition, each embarked member is assigned a fixed lifeboat $\tilde{b}^f = (\tilde{b}^f_1, \tilde{b}^f_2, \ldots, \tilde{b}^f_n)$.

The objective of this work is to establish an initial position $\tilde{p}^k$ and a boat assignment $\tilde{b}^f$ for the embarked members to minimize the ship's evacuation time,

$$t^{op} = \min t^{ev}(\tilde{\omega}_{\tilde{p},\tilde{b}}) = \min\max\left\{ T_i(\tilde{\omega}_{\tilde{p},\tilde{b}}), i = 1, \ldots, n \right\}; \tag{6}$$

that is, we seek the optimal route set $\tilde{\omega}^{op}_{\tilde{p}^k,\tilde{b}^f}$ such that

$$\tilde{\omega}^{op}_{\tilde{p}^k,\tilde{b}^f} = \arg\min\left\{ t^{ev}(\tilde{\omega}_{\tilde{p},\tilde{b}}),\ \tilde{\omega}_{\tilde{p}^k,\tilde{b}^f} \in \widetilde{\Omega}_{\tilde{p}^k,\tilde{b}^f} \right\}. \tag{7}$$

The ship evacuation dynamic monitoring system (SIMONE) is a prototype software, developed within the framework of a doctoral dissertation at the Universidad Politécnica de Cartagena (UPCT) in Spain, implementing this optimization problem. SIMONE simulates complex process system integration, as described above. Its main contribution is that it provides an optimal evacuation engine for a contingent embarked on a military ship. Thus, this engine recalculates a network of alternative escape routes in the event of an indefinite breakdown occurring in real time, monitoring the movement of the contingent at all times by using decision support techniques to achieve evacuation in the shortest possible time.

SIMONE is thus a simulator modeling a dynamic structure emulating the general layout of a warship that has suffered an unforeseen breakdown. An optimal evacuation process is determined for the members of the crew (agents) in the shortest possible time. To automate the configuration of a scenario (fire, structural damage, smoke, heat, etc.) and control and monitor the people on board, it is essential to integrate the fundamental information provided by the different systems through a communications gateway.

To emulate the automation of the environment, run the simulation of the evacuation, track the results, and make decisions; that is, to implement the functionality of the developed system, the following sequence of steps must be carried out.

- Loading the scenario model, consisting of a file containing the features of the ship scenario or environment (graph). Instantiation of the dynamic structure on which the simulation process will be executed.
- Loading the agent configuration and file of registry fields, including the configuration attributes of the instantiated agents that emulate the members of the embarked contingent interacting with the simulation scenario.
- Processing disabling locations of the simulation scenario and blocking the nodes of the instantiated dynamic structure, emulating disabled premises or transit areas due to a sudden breakdown.
- Executing the embarked population evacuation, including interaction among the different objects, emulating the evacuation study process to ensure optimal and nondeterministic displacement of the agents throughout the dynamic structure.
- Generating a results file in an exportable format, necessary for further analysis.

4. Optimization Process

As previously stated, the optimization process is based on dynamic graphs modeling the reference platform and agents representing the embarked contingent. Once an agent is relocated, the resulting graph will show a different state and, therefore, it will be necessary to recalculate the state of the graph and the costs associated with each of its vertices. Thus, the cost of a vertex will depend on the structure of the graph and its state, represented by the location of the remaining agents.

Following the description above, the simulation engine attempts to move agents through the optimal routes identified, which are those that entail the lowest estimated cost. This evacuates each agent in the shortest possible time, minimizing the evacuation reference time or time recorded by the last evacuated agent, that is, the one who recorded the longest evacuation time.

Algorithm 1 shows the pseudocode of the recursive method estimating the cost of the different nodes of the graph representing the structure of the ship. Each node can host an indefinite number of crew members at a particular node during evacuation. As can be seen, the objective of the algorithm is to calculate the cost of all possible routes recursively. First, for each node of the graph, the cost of moving the agents through that node is accumulated. Next, if the node's estimated cost for that route is lower than the available cost, it will be used as a reference. Finally, this cost is added to each of the nodes to which the reference node is linked, and the cost estimation function is recursively called.

Algorithm 1: Estimation of the cost of the graph nodes representing the ship.

```
estimateGraphCostTravel($graph.node.edge.next, accumulatedCost$)
if not EndOfGraph then
    if graph.node.NotEmpty then
        /* Accumulates estimated cost of moving these members through
           the node                                                   */
        $accumulatedCost \leftarrow accumulatedCost + graph.node.crewMembers \times graph.node.cost$
    end
    if $accumulatedCost < graph.node.cost$ then
        /* In the event that the estimated cost of the node for this
           route is lower than the available one, this cost will be
           designated as reference                                    */
        $graph.node.cost = accumulatedCost$
    end
    foreach graph.node.edge do
        /* Adds the cost of the link accumulated to the estimated cost
           of the node                                                */
        $accumulatedCost = graph.node.cost + graph.node.edge.cost$
        /* The function is called recursively indicating the node
           of the next link and the estimated cost so far             */
        estimateGraphCostTravel($graph.node.edge.next, accumulatedCost$)
    end
end
```

The MaritimeEXODUS application initially solves the problems and lack of suitability of the proposed LP model. However, this simulator does not have the capacity to set the minimum time employed in the evacuation process as an objective function. Therefore, to address the optimal cost function that best suits an agent continuously supported when choosing one route or another, the shortest travel time to the agent's lifeboat should be considered, not the shortest distance. SIMONE does this. Moreover, SIMONE not only recommends the displacement of an agent following the quickest route but its estimated cost computation includes the agent's waiting times identified along a route. The estimated cost makes it possible to anticipate congestion, thus avoiding deadlock situations caused by a number of agents competing for the same resource.

5. Results

To validate the results, the outcomes provided by SIMONE are compared with the results obtained using MaritimeEXODUS, as it is recognized as a validation tool by current regulations.

The simulations executed in both simulators for the same scenario revealed aspects that gave us insight and a better understanding of the evacuation problem. They are listed below.

1. Contrary to what we initially expected, the evacuation process is not influenced very much by the size of the simulated population or its relocation throughout the simulation scenario.
2. Congestion due to a large influx of agents to a specific space at the same time (see Figure 3) greatly affects the total evacuation time, slowing it down or even causing

a massive deadlock. In the case of MaritimeEXODUS, this paralyzes the execution of the process.

3. The method implemented in SIMONE to address optimal evacuation is based on the distribution of agents (load balancing) along the optimal routes identified (see Figure 3), thus ensuring that their estimated cost (time) is equalized.
4. The optimal distribution of agents throughout the optimal evacuation routes results in less congestion and, thus, a decrease in waiting times, also reducing evacuation times and the length of the evacuation.
5. The total time of an evacuation process is determined by the evacuation time employed by the last agent to evacuate the simulation scenario.
6. The process of executing an evacuation on a platform that dispenses a complete network of routes has a longer execution time (95 ± 10 s) than the same process executed on the same network (75 ± 10 s) as a result of a failure. The configuration of damage is emulated by disabling those vertices of the dynamic graph that correspond to the spaces of the scenario affected or inoperative due to the breakdown.
7. Disabling vertices simplifies the dynamic graph that emulates the scenario and, in view of the results, the reduction of the dynamic graph is greater when the damage caused by a failure is more significant. Thus, the corresponding simulation presents a lower computational load and less processing time.

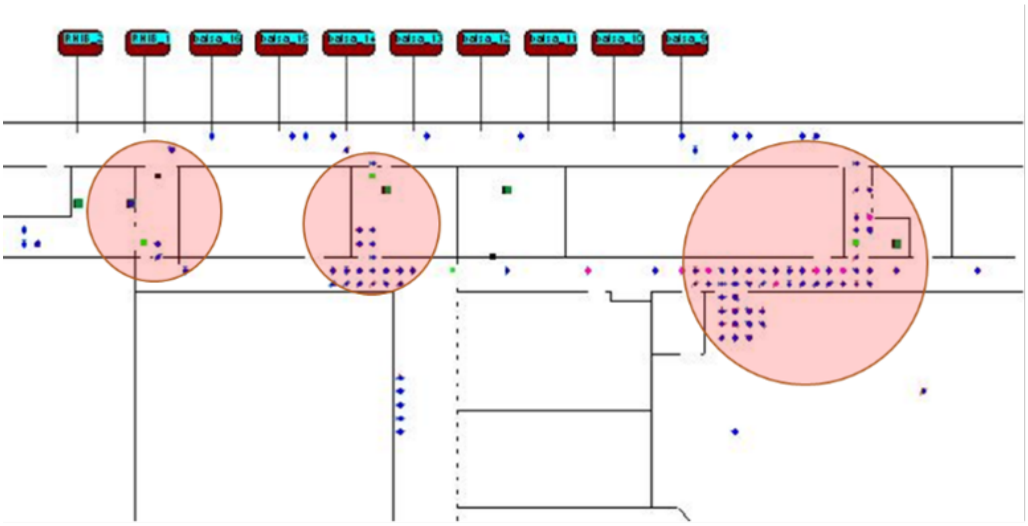

Figure 3. Unbalanced agent congestion at exits to exteriors, evacuation process (source MaritimeEXODUS).

5.1. Simulation of an Intact or Undamaged Platform

A total of 68 simulations of the abandonment process were executed for both simulators on the study platform scenario without any failure or incident. Simulations followed the evacuation protocol established by the Spanish navy doctrine on the network of preestablished routes.

The range of programmed simulations included the following two starting situations.

1. The call to general quarters (GQ), wherein crew members occupy their corresponding combat positions, and the embarked contingent occupies the locations designated for this particular event.
2. *Night transit at three patrols and rough seas* (three teams watch, 3TW). This starting situation has been identified as the worst possible case study due to the complexity of the scenario [14]. This case places a third of the crew on duty, and the remaining crew and the onboard contingent are located in premises, cabins, or decks set up for rest.

Figure 4 shows the resulting evacuation times obtained from the simulations carried out by both simulators (MaritimeEXODUS and SIMONE) for the specific starting situations 3TW and GQ.

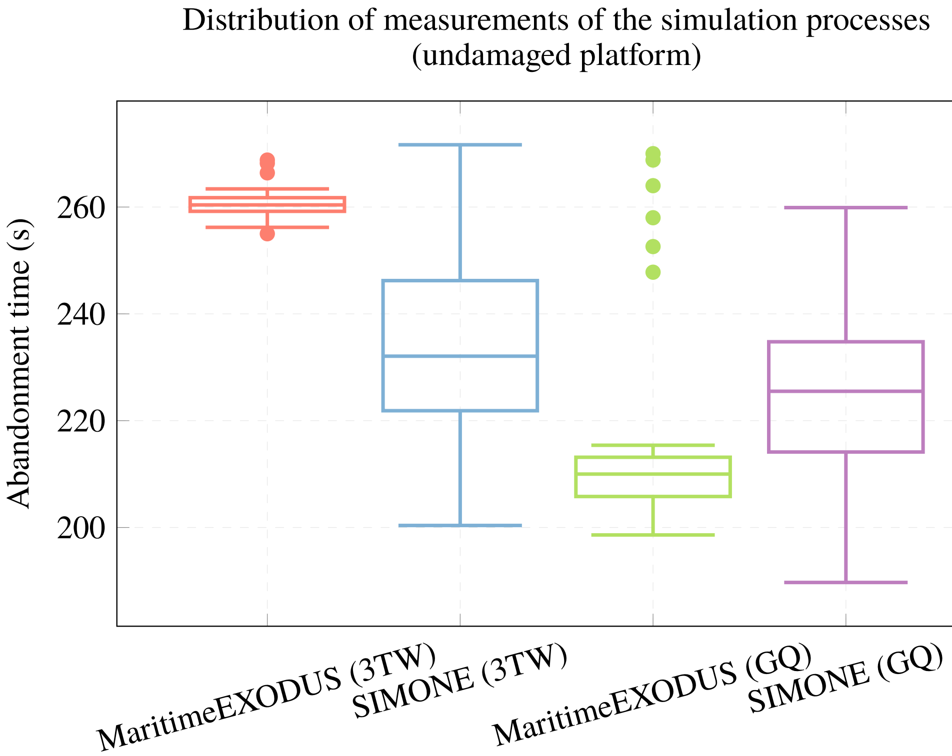

Figure 4. Box plots, abandonment times (MaritimeEXODUS vs. SIMONE) for the starting situations GQ and 3 TW in an undamaged platform.

Based on the evacuation times achieved for the GQ starting situation, the following observations are pertinent. As it is a regulated protocol rehearsed by the embarked population, the value of the median evacuation times obtained from the nondeterministic simulators MaritimeEXODUS and SIMONE are very similar (210 s, 225 s, respectively) despite the significant dispersion they show. The GQ assumption alludes to an ideal situation, wherein the members of the embarked population are in predefined positions and evacuate the platform through a network of unscathed routes. Thus, the evacuation process is agile (see Figure 5), and the times recorded are shorter. However, this situation is extremely unlikely to occur in reality.

Regarding the GQ assumption, it should be noted that MaritimeEXODUS was configured to minimize crew evacuation times by predefining optimal routes through LP. The objective was to compare its performance in the best possible conditions against SIMONE. That is why better results are obtained only for this ideal case. Even so, SIMONE can achieve minimum evacuation times lower than those of MaritimeEXODUS. In summary, MaritimeExodus does not provide better results in any case except one if the optimal route preconfiguration is done through LP. This is very impractical because the situation in which this case occurs has practically zero probability of occurrence.

Regarding the evacuation times obtained for the 3TW starting situation, the following remarks can be made. Because most of the members of the embarked population start from very specific decks, a significant delay at the beginning of the evacuation process should be taken into account as a consequence of the reaction times and evacuation preparation this specific situation entails. This time is not included in the results of the simulations and ranges between 3 and 4 min. It is worth noting that the concentration of agents on the starting decks before their evacuation inevitably leads to congestion at the accesses. Thus, these common locations on specific decks have higher than average occupancy rates or agent concentration. This calls for equalizing the estimated costs at these initial congestion points (accesses) by distributing agents among the accesses of the starting ship decks. Optimal management seeks progressive agent evacuation throughout the entire process (see Figure 6), minimizing the time spent by each agent and, thus, the time spent by the last agent leaving the platform. Under this assumption, a significant difference between the nondeterministic simulators MaritimeEXODUS and SIMONE is identified (Figure 4). Thus, the optimal management implemented in SIMONE provides a competitive advantage, increasing an embarked population's probability of survival by reducing median evacuation times (260 s, 232 s, respectively).

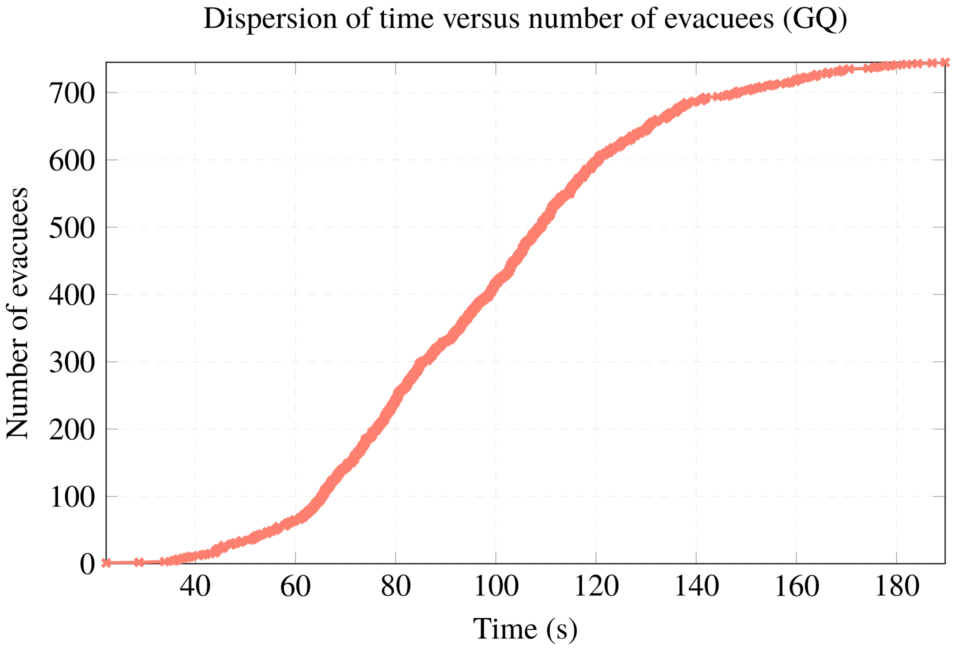

Figure 5. Dispersion diagram, time per number of evacuees (GQ situation, SIMONE).

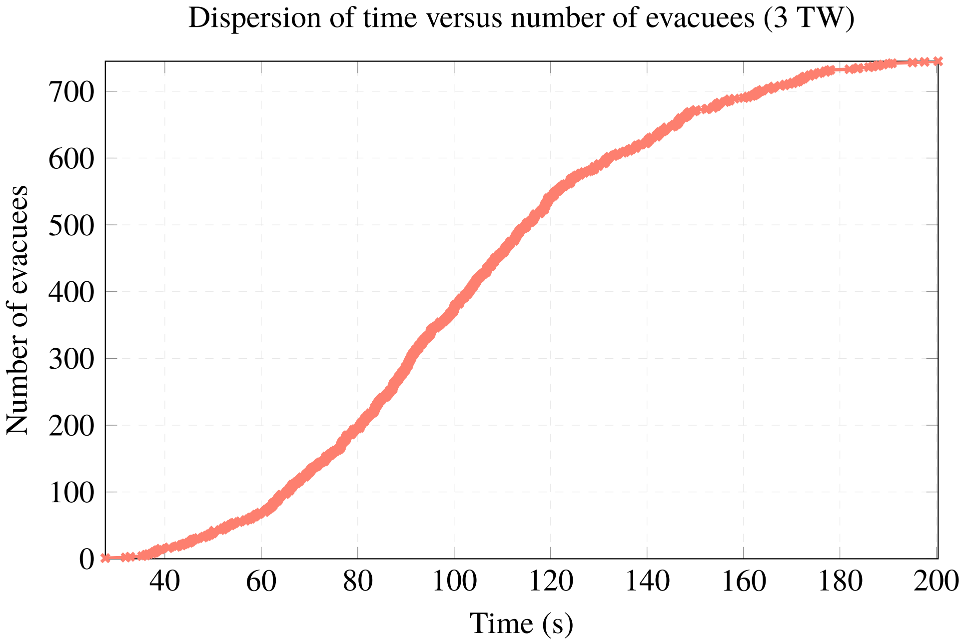

Figure 6. Dispersion diagram, abandonment time per number of evacuees (3 TW, SIMONE).

Considering the evacuation times (Figures 5 and 6) provided by SIMONE for an embarked contingent of 745 people, clear differences are identified between the evacuation times of the GQ and 3TW situations. The optimal management implemented by SIMONE appears to show an advantage for the GQ starting situation, which can be interpreted as an increased probability of survival.

5.2. Platform Simulation with Focused Failure

Sixty-eight simulations of the abandonment process were executed by both simulators on the dynamic graph emulating the platform under study, whose coincident vertices with the main ladder from bow to port were disabled as a result of the failure we configured. Likewise, the analysis of the starting situations of GQ and 3TW were addressed.

The following diagrams (see Figure 7), show the resulting evacuation times achieved by both simulators (MaritimeEXODUS and SIMONE) for the specific GQ and 3TW starting situations.

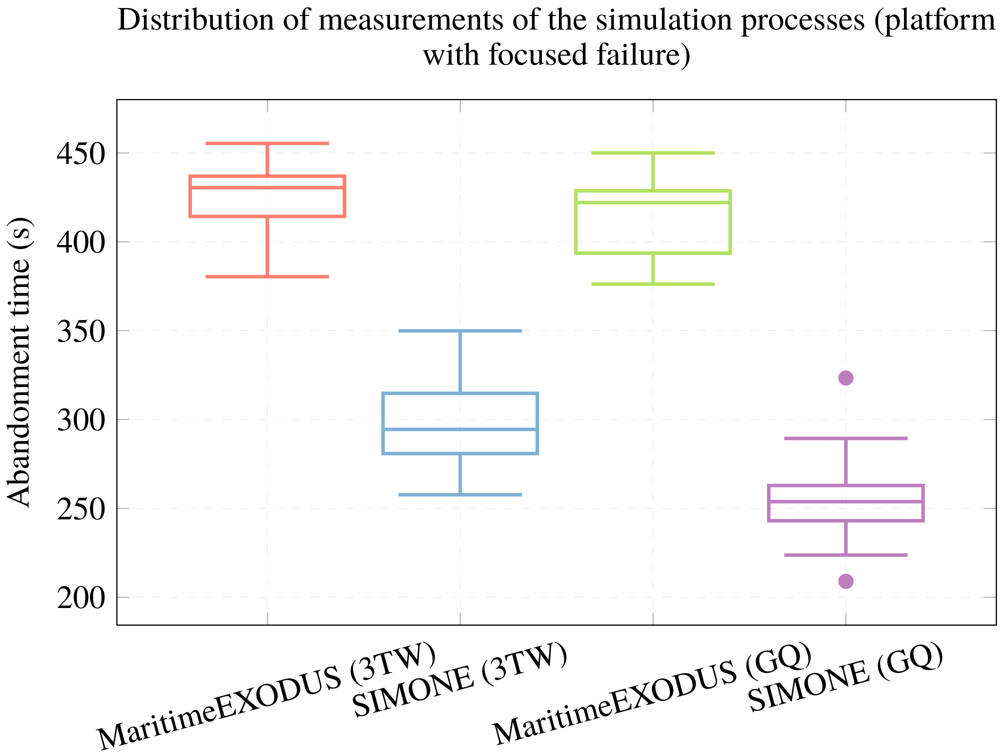

Figure 7. Box plots, abandonment times (MaritimeEXODUS vs. SIMONE) for the 3 TW and GQ starting situations.

The evacuation times obtained for the starting GQ situation show the following. It is a regulated protocol, repeatedly rehearsed by the embarked population. However, Figure 7 illustrates that the value of the median evacuation times obtained from the MaritimeEXODUS and SIMONE simulators are noticeably different (422 s, 253 s, respectively), as well as their corresponding dispersion. It should be noted that the GQ assumption alludes to an ideal situation where the members of the embarked population are located at certain predefined positions, although under this assumption, the network of routes is significantly affected by the configured fault. This reduces the agility of the evacuation (see Figure 8) compared to the same starting situation without breakdowns (as shown in Figure 5).

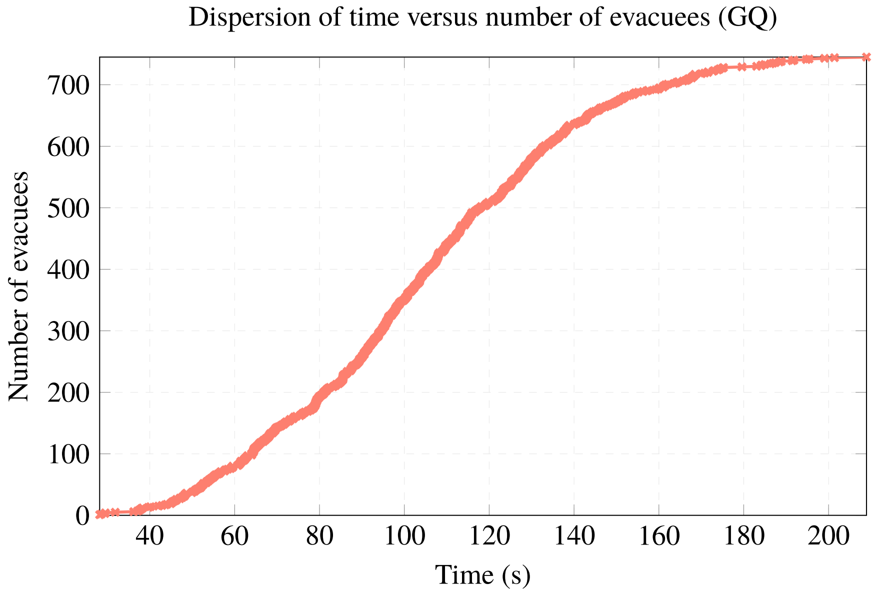

Figure 8. Dispersion diagram, time per number of evacuees (GQ situation, SIMONE).

Regarding the evacuation times attained for the 3TW starting situation, the following comments can be made. Once again, most of the members of the embarked population start the evacuation from very specific decks. This causes delays at the beginning of the process in terms of reaction times and preparation for evacuation. This estimated time is not included in the results of the simulations. We also identified agents crowded on the departure decks waiting to evacuate, inevitably leading to congestion at the accesses. Therefore, these common locations of specific decks show disproportionate occupancy rates. This situation calls for optimal management to distribute the agents among the accesses of the starting ship decks to equalize the estimated costs at the congestion points (accesses). This means progressively evacuating agents throughout the entire process (see Figure 9), minimizing the time taken by each agent and, thus, the time spent by the last agent leaving the platform. A significant difference between the results achieved by MaritimeEXODUS and SIMONE is observed (see Figure 7), showing the competitive advantage of the SIMONE algorithm. SIMONE increases the probability of survival by reducing median (430 s, 294 s, respectively) evacuation times.

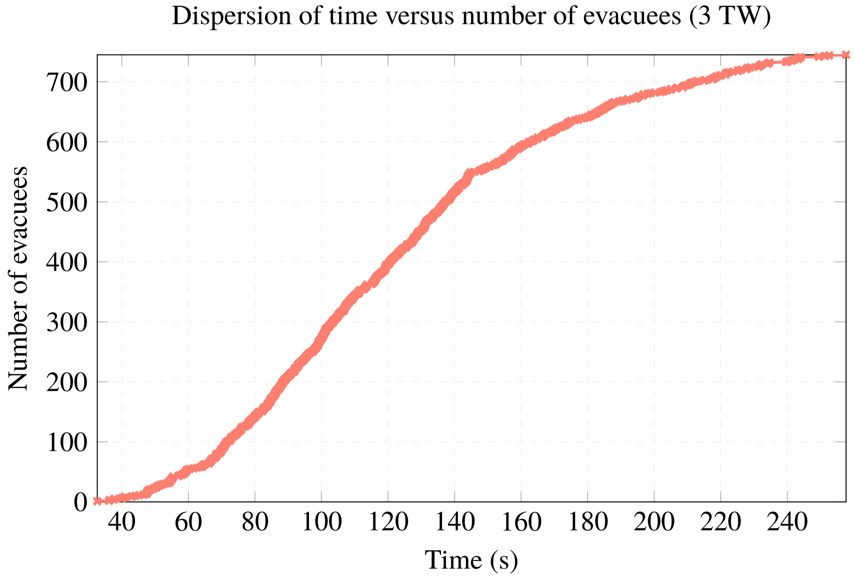

Figure 9. Dispersion diagram, abandonment time per number of evacuees (3 TW, SIMONE).

We can conclude that, based on the evacuation times (see Figure 7) provided by MaritimeEXODUS and SIMONE, there are notable differences between the evacuation times of the GQ and 3TW study cases. The optimal management implemented by SIMONE provides a great competitive advantage that leads to a notable increase in the probability of survival for the embarked population.

5.3. Platform Simulation with Generalized Failure

The MaritimeEXODUS simulator is not applicable to this generalized failure case. Once the MaritimeEXODUS was discarded, 68 simulations of the abandonment process were run on the SIMONE simulator addressing the starting situations of 3TW and GQ. The resulting evacuation times are plotted in Figure 10.

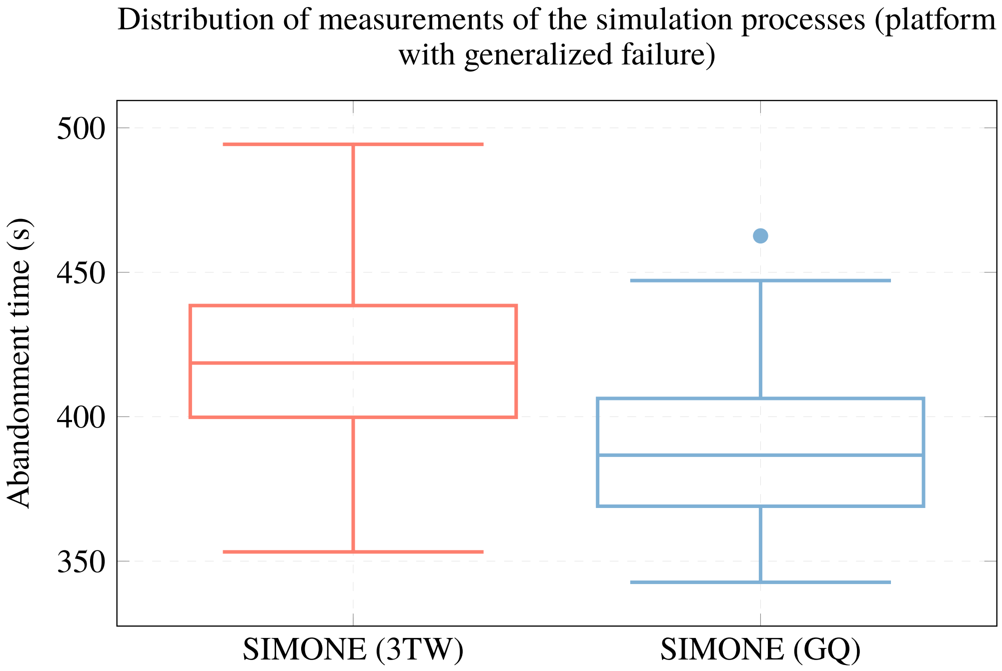

Figure 10. Box plots, abandonment times (SIMONE) for the 3 TW and GQ starting situations.

The evacuation times achieved for the GQ starting situation (see Figure 10) show that as it is, a regulated protocol, rehearsed by the embarked population, a significant alteration of the escape route network can be observed (Figure 10). This causes SIMONE to show a very wide range of evacuation times (120 s). The extensive alteration of the network of escape routes results in a very short median evacuation time (387 s). The generalized breakdown is configured as a serious restriction on the dynamic graph emulating the simulation scenario. Thus, the elimination of the most complex blockages occurring at certain points in the scenario (outdoor accesses) in the previous simulated cases is confirmed. In this case, only the management of massive congestion is identified at the accesses of the ship's superstructure.

Unlike MaritimeEXODUS, SIMONE does not implement agents competing for available resources, based on the assumption that training and military instruction effectively reduce panic in emergency situations. We should remark that the GQ assumption refers to an ideal situation in which the members of the embarked population are located at predefined positions. Although under this assumption their route network is greatly affected, most of the embarked population runs through fault-free zones. This influences the agility of the evacuation (time) whereas the rest of the population experiences blockages, causing the evacuation process to lengthen to apparent maximum times (see Figure 11), with the simulation of a minor failure (see Figure 8).

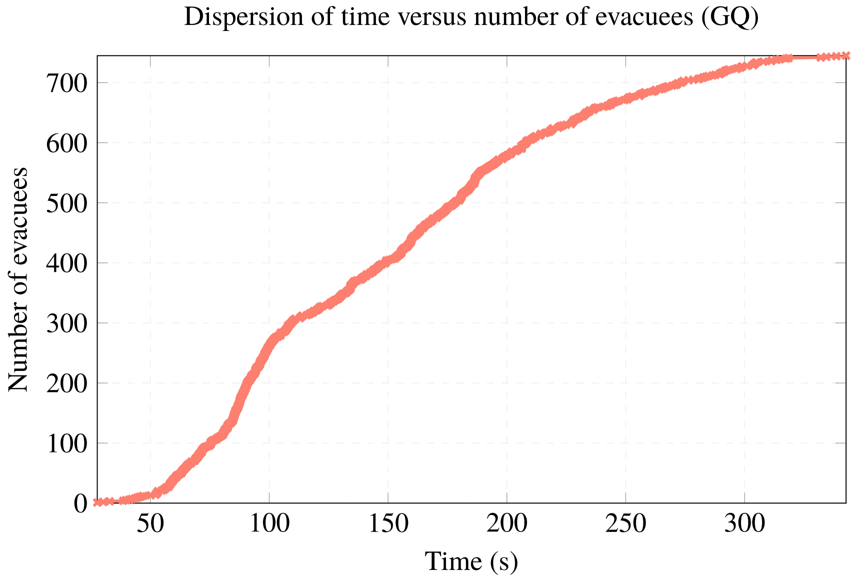

Figure 11. Dispersion diagram, time per number of evacuees (GQ situation, SIMONE).

Examining the evacuation times obtained for the 3TW starting situation, the following additional comments can be made. The delay estimated at the beginning of the process due to reaction times and preparation for evacuation is not included in the simulations. Because most of the population depart from specific areas, crowding at the accesses from the decks of the superstructure is unavoidable and disproportionate after disabling the port accesses as a result of the configured fatal failure. This inevitably increases evacuation times. The optimal management implemented evenly distributes the agents, based on the estimated evacuation costs, among the enabled accesses. Thus, it seeks the continuous evacuation of agents throughout the process (see Figure 12), minimizing the time spent by each agent and the time taken by the last agent leaving the platform. In this situation, the network of routes is greatly affected, although most of the embarked population move through areas free of breakdowns. This influences the agility of the evacuation, with increasing median evacuation times (419 s (see Figure 10)). The rest of the population is delayed, causing evacuation process to lengthen to apparent maximum times (see Figure 12) with the simulation of a minor fault (see Figure 8).

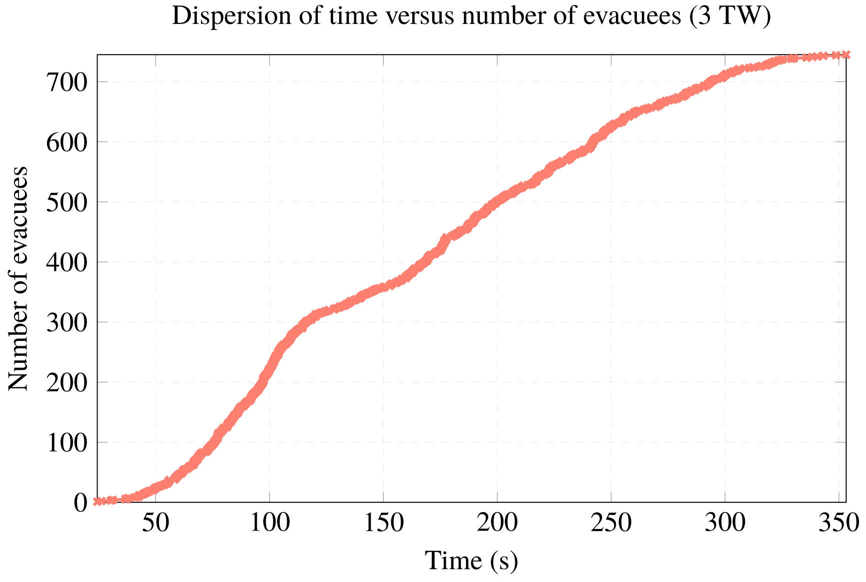

Figure 12. Dispersion diagram, abandonment time per number of evacuees (3 TW, SIMONE).

According to the evacuation times provided by the SIMONE simulator (see Figure 10) in the study of the GQ and 3TW cases, the optimal management implemented appears at first to be a disadvantage, with much longer evacuation times provided by SIMONE in the event of a minor fault (see Figure 7). This would result in a notable decrease in survival probabilities. However, given the circumstances and the magnitude of the damage suffered, SIMONE is capable of presenting a plausible evacuation solution for the survival of the crew within the formulated times.

6. Conclusions

In view of the results obtained, SIMONE has proven to be a powerful optimization tool for the evacuation process on board a warship. The options for moving an agent depend on the situation or state of the simulation environment as well as on the other agents involved in the evacuation. This premise provides better outcomes than the MaritimeEXODUS, which lacks this capability and only monitors the intervening agents based on preestablished routes or the erroneous criterion of the shortest path (distance).

Moreover, based on the professional skills of an embarked military population, SIMONE does not implement interlocks, which occur in the MaritimeEXODUS application of reference. In cases of massive interlock, this seriously jeopardizes the simulation process. SIMONE uses structures supported by queuing theory to simulate congestion and randomly takes an agent, thus emulating the allocation of resources used by that agent.

The optimal management implemented by SIMONE leads to a progressive evacuation of the embarked population, delimited by a linear slope, as shown in Figures 5, 6, 8, 9, 11 and 12, which depends on the limitations caused by the congestion produced in the simulation scenario.

Regardless of the results achieved by both simulation tools in the different study cases, the current applicable regulations have been validated in terms of the maximum evacuation times required for the naval ship under study. Likewise, SIMONE's functional approach optimally addresses an evacuation process in a sudden failure scenario in real time, wherein the capabilities of the pre-established escape route network could be seriously affected or disabled. This results in a notable increase in the probability of its embarked population's survival.

Author Contributions: Conceptualization, H.M.-G. and R.A.-C.; methodology, J.G.-H.; software, H.M.-G.; validation, R.A.-C., A.-J.G.-S. and J.G.-H.; formal analysis, H.M.-G.; investigation, H.M.-G.; resources, A.-J.G.-S.; data curation, J.G.-H.; writing—original draft preparation, H.M.-G.; writing—review and editing, R.A.-C.; visualization, R.A.-C.; supervision, J.G.-H.; project administration, J.G.-H.; funding acquisition, A.J.G.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by MCIN/AEI/10.13039/501100011033 grant number PID2020-116329GB-C22 and grant number TED2021-129336B-I00. This work is also a result of an internship funded by the Autonomous Community of the Region of Murcia through the Fundación Séneca-Agencia de Ciencia y Tecnología de la Región de Murcia (Seneca Foundation—Agency for Science and Technology in the Region of Murcia) and European Union NextGenerationEU program.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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