Prediction of Emergency Preparedness Level On-Board Ships Using Discrete Event Simulation: the Case of Firefighting Drill

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This paper proposes a hybrid approach, including Fuzzy Dematel (FD) integrated with Discrete Event Simulation (DES), to predict emergency preparedness levels on-board ships. The FD used critical factors that affect emergency preparedness to conduct a DES based on real firefighting drill records collected from 45 merchant ships. The simulation results showed the average duration of on-board drills in ideal conditions (27.47 min.), in the worst-case scenario (51.49 min.), for Ship A (29.99 min.), and Ship B (28.12 min.). Based on the findings, recovery actions linked to the factors have been recommended to promote on-board implementation. The proposed model is of great importance to shore-based managers, allowing them to monitor the emergency preparedness level of the fleet continuously, even during pandemics. Further studies are planned to develop a remote monitoring system that would digitalize the existing response procedures in emergency situations.

KEY WORDS

~ Ship emergency preparedness
~ Firefighting drill
~ Discrete event simulation
~ Fuzzy Dematel

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1. INTRODUCTION

Maritime transportation has been affected by the outbreak of COVID-19 (Choquet and Sam-Lefebvre,2021). In particular, execution of ship operations has been drastically modified due to quarantine (Dorofeev et al.,2020) and port restrictions (Desmonda,2020). Since the operating environment at sea is harsh and challenging, unanticipated faults and events might result in the loss of vessels, cargo damage, environmental pollution, and even poor market reputation (Thieme and Utne,2017; Soares and Teixeira, 2001). The International Maritime Organization (IMO) has extended regulations to reduce risks in ship operations (Karahalios,2018). Despite the various obstacles, shipping accident rates at sea are still a focal issue for the maritime society (Celik et al., 2010). Apart from accidents, emergency situations, near-miss events, and hazardous occurrences also require prompt action (Kwok et al., 2019). However, there is still considerable concern and research potential especially with respect to ship emergency preparedness (Tac et al., 2018-a).

In recent years, maritime literature has paid particular attention to oil spill and prevention studies. (Lin et al.,2013; Santos et al.,2013; Knol and Arbo,2014; Huntington et al.,2015; Aguilera et al.,2016; Liao et al., 2012; Afenyo et al., 2017; Ivanova,2011; Castanedo et al.,2006; Palsson et al.,2018). Moreover, a number of studies have focused on emergency preparedness in the supply chain (Markmann et al.,2013; Kwesi-Buor et al., 2016; Asgari et al.,2015; Pitilakis et al., 2016; Wood et al., 2002; Hale and Moberg, 2005). The conducted research on emergency preparedness at offshore facilities has mainly targeted personnel transfer and evacuation (Brachner and Hvattum,2017; Wang,2002; Musharraf et al.,2016; Musharraf et al.,2018; Ping et al.,2018; Cheng et al.,2018). Indeed, human behaviour in emergency situations is another focus of researchers (Akyuz,2016; Lee et al., 2003; Woodcock and Au,2013, Karahalios,2017). On the operational level, the role of drills and exercises in ship emergency management is dealt with in several studies (Wu et al.,2014; Beerens and Tehler,2016; O'Brien,2003). According to Kwok et al. (2019), organizations often conduct safety drills to ensure effective response actions, team integrity, and procedural improvements. Tac et al. (2018-b; 2020) evaluated and benchmarked the critical factors influencing ship emergency preparedness based on WEKA and DEMATEL techniques. Although there are studies where shipboard emergencies were subjected to factor analysis, studies that simulate emergency drills using real time data are very limited.

Considering the gaps in literature, this paper aims to predict ship emergency preparedness levels in different scenarios. To achieve this, the existing studies on factor identification Tac et al. (2018-b; 2020) are extended with Discrete Event Simulation (DES) applied to firefighting drill records. This section presents the motivation behind this study and gives a brief overview of literature. Section 2 explains the theoretical background of the study. Section 3 demonstrates the simulation of firefighting drills on board. The final section provides the theoretical and practical contributions of this study.

2. METHODOLOGICAL BACKGROUND

2.1. Fuzzy Dematel technique

The FD technique identifies relationships between factors and determines the criteria for relationship types and the severity of their effect on each factor (Akyuz and Celik,2015; Wu and Lee,2007; Wu,2012). The main advantage of fuzzy sets integrated Dematel is that it takes into account the condition of the fuzziness and is flexible in fuzzy situations (Wu,2012). A Fuzzy Dematel is applied in eight steps (Akyuz and Celik,2015; Tac, 2019; Tac et al., 2020): Step 1 - Coordinate a group of experts, Step 2 - Determine factors and construct fuzzy scale, Step 3 - Obtain evaluation of the group decision-makers, Step 4 - Construct normalized direct-relation fuzzy matrix, Step 5 - Calculate total-relation fuzzy matrix, Step 6 - Analyse the structural model, Step 7 - Defuzzification, Step 8 - Build up cause-effect relation diagram.

2.2. Discrete-event simulation

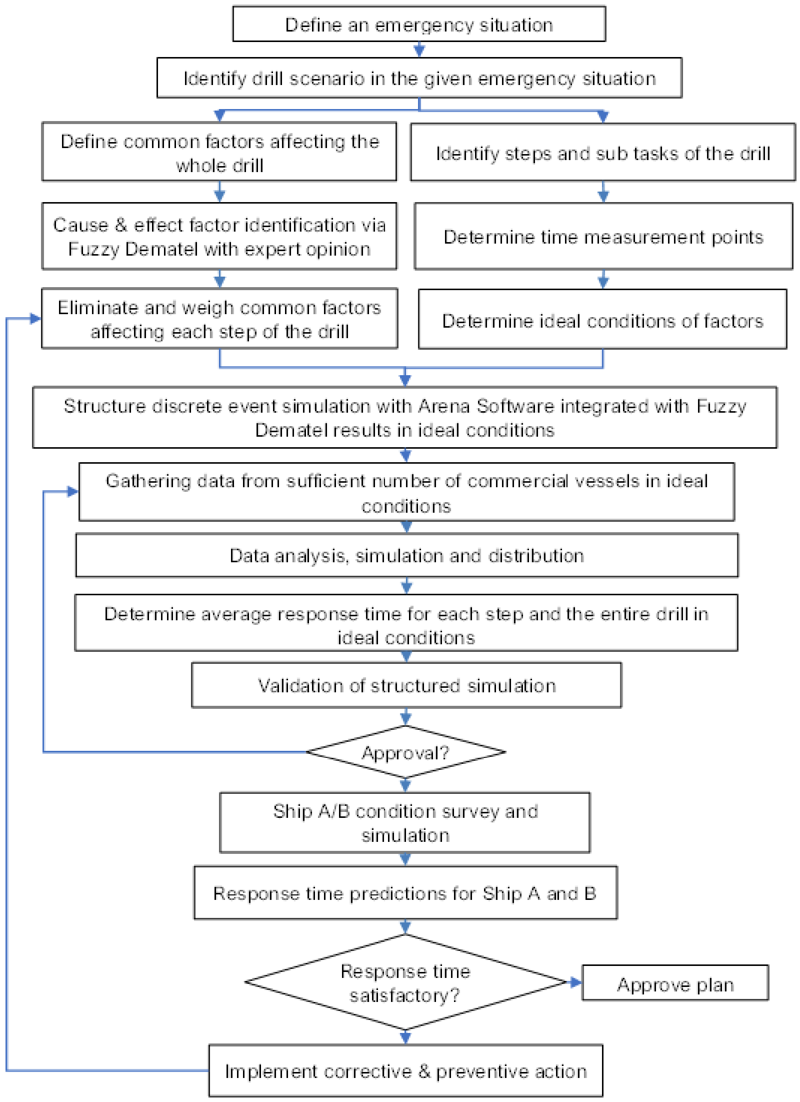

Figure 1. Flow diagram of the proposed hybrid approach

Simulation is the imitation of the operation of a real-world process or system over time (Shawki et al., 2015). Simulation modelling has been used in various fields where analytical models cannot be used due to the complex nature of problems (Almaz and Altiok,2013). DES is an important tool for studying different types of systems which can be used in public services, healthcare, manufacturing, call centres, logistics and many other situations (Chwif et al.,2013). DES is primarily defined as a model that simulates events that occur in sequences, describing their influence on other events (Frough et al.,2019). According to Allen (2011), DES might enable people to assess their systems and perceive efficiency gains. It allows system operation modelling as a discrete sequence of events in a timely manner. Simulation may also jump directly from one event to another since there is no change between consecutive events (Sharma,2015). The simulation process consists of scope determination, data collection, data analysis, model structuring, verification, experimental studies, visualization, etc. Several software packages with easy to use interfaces have been developed (Yılmaz,2018), such as the Arena Simulation Software (Pegden and Davis,1992). Arena is a tool that allows easy and rapid modelling, allowing the user to combine constructs of several application-focused templates. The advantage of Arena over other simulation tools is the ease of data entry and flowcharting methodology for modelling (Shawki et al., 2015). Furthermore, the Arena simulation software has been used in maritime research such as for analysing vessel traffic, port performance and investment, freight transport, and the impact of decisions (Almaz and Altiok,2013; Lin et al.,2014; Cortes et al., 2007; Iannone et al., 2016; Rahimikelarijani et al.,2018; Na and Shinozuka,2009). Figure 1 gives the flow diagram of the proposed hybrid approach, including FD integrated with DES to predict ship emergency preparedness level on-board ships.

3. FIREFIGHTING DRILL SIMULATION

3.1. Model construction

Firefighting drills and exercises are significant elements of the safety management system. A firefighting drill consists of the following 13 steps Tac et al. (2019): 1. sounding the fire alarm, 2. announcing the fire through the public address system, 3. mustering, 4. enumeration, 5. donning a fire suit, 6. putting on the breathing apparatus, 7. starting fire pumps, 8. preparing/pressurizing fire hoses, 9. isolating electrical supply, 10. closing fans, ventilations and watertight doors, 11. entering the fire zone in a safe and logical way and successfully extinguishing the fire, 12. initiating the cooling process employing sea water, 13. putting back the equipment used in the drill. The firefighting drill was modelled in the Arena software to analyse average response times. The proposed model has been demonstrated with four different scenarios: i) ideal shipboard conditions, ii) worst-case scenario, iii) ship-A operational situations, iv) ship-B operational situations. Ideal shipboard conditions are defined as the absence of any factor that could have a negative effect on drill duration. The layout of the initial model structured in ideal conditions is shown in Figure 2. The model has been built based on the following assumptions: i) no interruptions during the drill, ii) no step should be skipped.

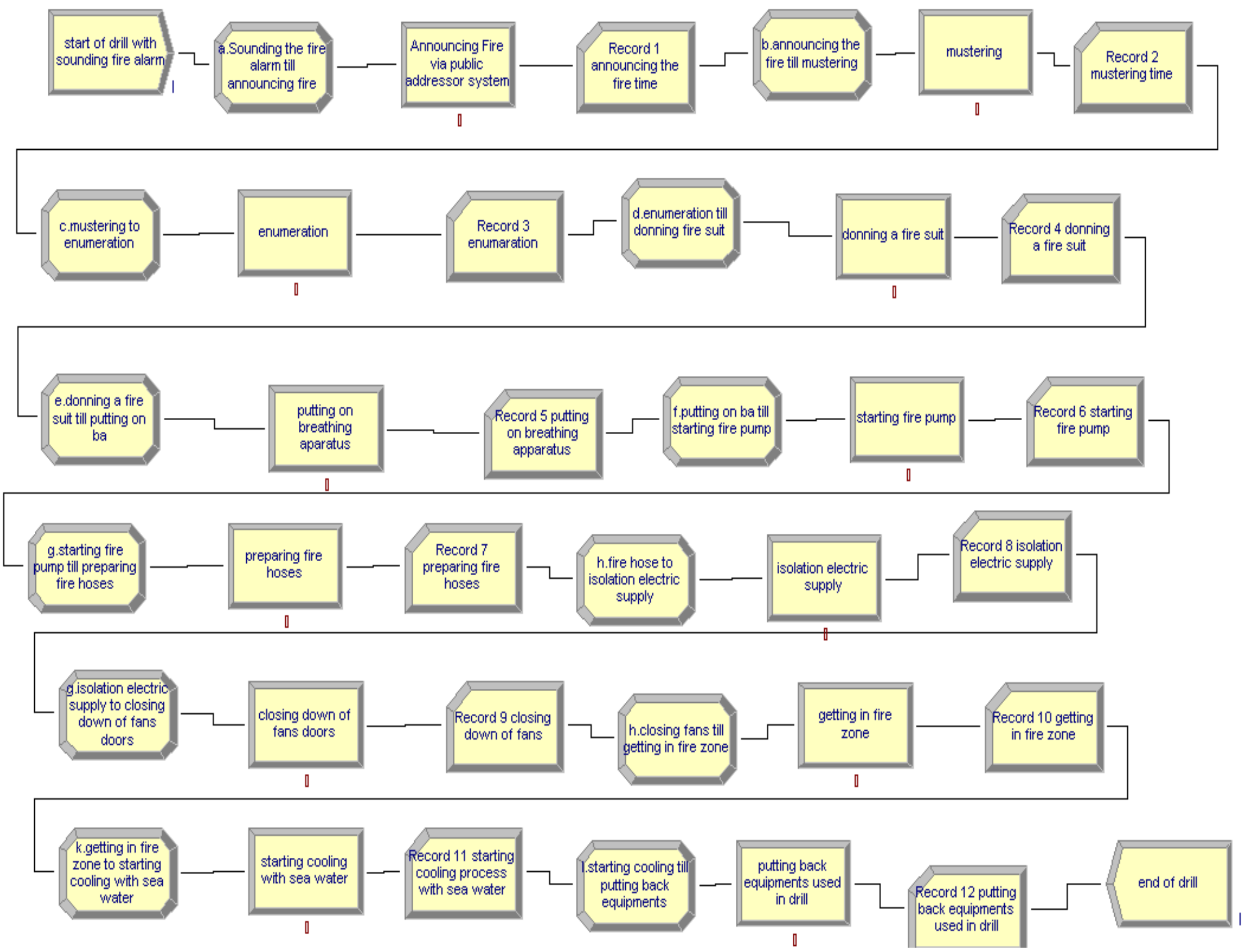

Figure 2. Simulation model built by Arena

There is one entry in the system. The CREATE module was used to simulate the drill that starts with the fire alarm. The period between fire detection and the sounding of the fire alarm has been ignored. Then, each step of the fire drill was simulated using PROCESS modules. Table 2 gives more detailed information on the process module. Finally, the DISPOSE module was assigned when the equipment used in the drill was returned to its initial position. This denotes that the drill has been completed.

3.2. Data collection

The next step was collecting required data for the model. A number of ship management companies were asked about the duration of the drills on their fleet's vessels. Sizeable feedback for 45 commercial vessels was obtained. Out of 45 vessels, 15 were bulk carriers and the remaining 30 vessels oil tankers. Ship managers were asked to provide information on the duration of each predefined firefighting drill step, as measured during real life firefighting drills. Firefighting drills were most frequently conducted in galleys (N=9) and manifold areas (N=8), followed by paint stores (N=5), engine rooms (N=5), pump rooms (N=5), and officers' mess rooms (N=4). Other places included the bridge, garbage station, mast riser and laundry room. One of the drills carried out on the fore deck was ignored not to affect analysis, due to the different length of the vessels which can affect drill duration.

Following data collection, outlier analyses were carried out using Minitab statistical software, version 18.1. An outlier can be defined as an ‘‘observation that deviates so much from other observations as to arouse suspicion that it was generated by a different mechanism (Hawkins, 1980)’’. The presence of outliers in a dataset can dramatically undermine the analysis and any subsequent results based on the data (Thennadil et al.,2018). After outlier analyses have been carried out, the Input Analyzer tool in Arena was utilized for distribution fitting.

Since the model has one entity, the statistics start from the beginning. The below formula (Toledo et al.,2003) was used to calculate the sufficient number of replications:

$$N(m) = \left(\frac{S(m)\, t_{m-1,1-\alpha/2}}{\bar{X}(m)\varepsilon} \right)^2 \qquad (1)$$

where Nm is the number of replications, S(m) is the data standard deviation, t is the test statistic obtained from the t-table, m is the number of initial replications that was assumed to be 10, α is the confidence interval of 90%, X(m) is the data mean and £ is the allowable percentage error. The allowable error percentage of 10% with t9; 0:95 equals 1.833. **Table 1-2** shows calculations based on 10-11 replications respectively.

Rep.	1	2	3	4	5	6	7	8	9	10	Mean	SD	N
Min	32.7	25.1	32.9	22.3	28.4	29.7	20.6	21.2	29.4	32.5	27.48	4.84	10

Table 1. Initial results for 10 replications

Rep.	1	2	3	4	5	6	7	8	9	10	11	Mean	SD	N
Min	32.7	25.1	32.9	22.3	28.4	29.7	20.6	21.2	29.4	32.5	27.48	27.35	4.607	11

Table 2. Initial results for 11 replications

3.3. Validation

Validation is concerned with the construction of the correct model. Validation, data collection and drill analysis were performed owing to the experts indicated in section 3.2. They checked the model with the authors to ensure that all the important components were included in the model, and were in the right sequence. After that, validation was conducted to ensure that the simulation model is as close as possible to reality. First, model results for ideal shipboard conditions were discussed with the experts based on their experience. Then, the actual system and the simulated model were compared. In this phase, the steady output of the model is usually compared to the real value obtained by data collection. To this end, the average duration of process 12 was selected since it also indicates total drill duration. The average obtained from 10 replications was 27.47455 minutes. The observed average duration of process 12 is 27.3456 minutes. Thus, based on the following calculation, the percentage error of the model is 0.47%. Considering 90% level of confidence, the model is valid.

$$\frac{\text{Average Time Real} - \text{Average Time Model}}{\text{Average Time Real}} = \frac{27.3456 - 27.4755}{27.3456} X\ 100 = \ 0.47$$

The structured initial model did not include any negative factor which could have an adverse effect on drill duration: that is, all data were gathered under ideal conditions. After running the model, the average firefighting drill duration was identified as 27.47 minutes.

3.4. Factor Identification

In factor identification, the FD analyse the generic factors that might affect drill performance. The list of the factors is as follows Tac et al. (2020): F1 pre-defined scenario and scenario realism, F2 lack of knowledge and education level of officers/engineers, F3 insufficient firefighting training and practice, F4 absent crew member, F5 absent supervisor, F6 lack of experience of crew member, F7 insufficient supervisor experience in rank, F8 no learning objectives defined in previous drills, F9 external factors (weather, sea conditions, wind, etc.), F10 poorly pre-defined tasks of crew members in the muster list, F11 poor safety culture and undisciplined use of personal protective/firefighting equipment and firefighting, F12 fatigue of crew members on board, F13 insufficient physical capability (age, weight), F14 crew member illness and health problems, F15 being under the influence of alcohol and/or drugs, F16 crew member reliability, F17 failure of firefighting/communication equipment, F18 neglected items in firefighting equipment routine inspection check list, F19 incorrect placement of portable tools, equipment or material in the firefighting system, F20 incorrect IMO labelling of firefighting equipment.

Clustering of factors affecting firefighting drills based on FD analysis is given in **Figure 3**. The analysis determined the cause and effect, as well as the level of influence of each factor. The factors affecting all predefined steps of an operational firefighting drill can be divided into two significant groups: cause and effect factors. Four of those factors stand out as frequently having a major impact on the drill. According to the analysis, F3 (insufficient firefighting training and practice) has the most significant influence on the performance of the entire drill. The second most important causal factor is F4 (absent crew member). The effect factors can be defined as those that are easily impacted by cause factors. Considering the importance of cause factors, effect factors can pose major challenges during the drill. F11 (poor safety culture and undisciplined use of personal protective/firefighting equipment and firefighting) has a major effect on the predefined steps of an operational firefighting drill. Likewise, F15 (being under the influence of alcohol and/or drugs) has significant effect on the predefined steps of an operational firefighting drill. The remaining cause and effect factors vary for each step of the operational firefighting drill.

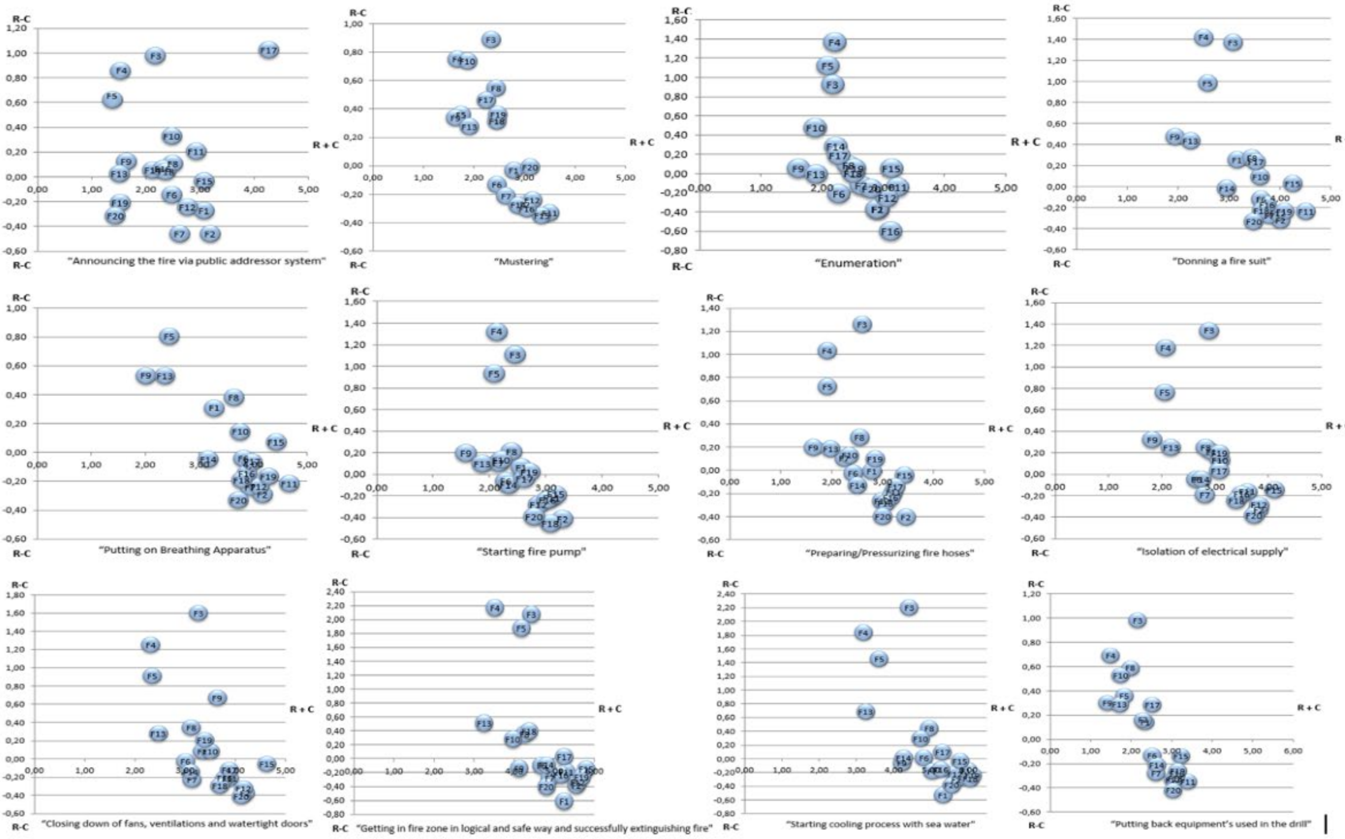

Figure 3. Clustering the influencing factors of firefighting drill based on FD analysis

3.5. Demonstrations and findings

The proposed model was demonstrated in four different situations: Case #1 (ideal conditions), Case #2 (worst case scenario), Case #3 (Ship A) and, Case #4 (Ship B). First, it was demonstrated under ideal conditions and real time data obtained from commercial vessels were used. Second, the worst-case scenario was constructed in accordance with FD results under the assumption that all generic factors are present during the drill. Last, the effectiveness of the model was tested by analysing and comparing two different field studies conducted onboard Ship A and Ship B with their real life drill durations. For purposes of the two case studies, ship management companies have been asked about the duration of drills onboard their fleet's vessels. They were asked not to submit data on drills which took place under ideal conditions, but only those where at least one of the mentioned generic factors was present. Shipping companies have also been asked about ideal conditions and to send reports on drills carried out under such conditions. The initial model was constructed based on these initial data using the Arena software. The results of demonstrations under ideal conditions and in the worst-case scenario are given in **Table 3**.

Third, the model was run for the operational situation of Ship A. The fire drill was conducted onboard an oil tanker in the Trinidad Anchorage area. The watchkeepers and 3rd officer could not participate in the drill. The 3rd officer had injured his hand when opening a water ballast tank manhole on board and suffering from the fracture of the tuft of the distal phalanx during the drill. Also, the vessel had been sailing between nearby terminals for 4 months; there had been violations of rest hours and/or work hours regulations. Therefore, fatigue has been accepted as another generic factor. In addition, a number of small holes in the fire hoses have been detected. Considering the exercise scenario, the following generic factors had effect in this case: illness and health problems of a crew member, fatigue, failure of firefighting/communication equipment.

Interval		Average	Min. Avg.	Max. Avg.
Process 1: Announcing the fire via the public address system	Ideal	0.7595	0.0111	2.9787
	Worst-case	1.2809	0.3772	3.3513
Process 2: Mustering	Ideal	2.8353	1.1481	3.8617
	Worst-case	5.3716	4.7835	6.2610
Process 3: Enumeration	Ideal	3.8118	2.3127	5.9031
	Worst-case	5.8228	3.2755	7.3748
Process 4: Donning a fire suit	Ideal	7.2715	4.2626	9.3772
	Worst-case	13.0169	7.8293	17.4774
Process 5: Putting on breathing apparatus	Ideal	7.6826	5.2967	11.3349
	Worst-case	15.3235	13.1547	18.7753
Process 6: Starting fire pump	Ideal	6.1255	1.9452	10.9083
	Worst-case	10.7228	7.7925	15.2378
Process 7: Preparing fire hoses	Ideal	7.1581	4.5861	10.7916
	Worst-case	15.2845	12.2671	17.4637
Process 8: Isolation of electric supply	Ideal	5.4762	3.0472	8.5500
	Worst-case	11.6574	8.6302	14.6549
Process 9: Closing down of fans	Ideal	5.9808	4.7669	7.5874
	Worst-case	11.9716	9.8956	14.5597
Process 10: Entering fire zone	Ideal	21.1631	13.2362	26.1211
	Worst-case	38.8127	30.7951	46.4212
Process 11: Starting cooling process with sea water	Ideal	11.7893	5.3106	18.3275
	Worst-case	26.2537	18.8298	38.2978
Process 12: Putting away equipment used in the drill	Ideal	27.4723	20.5516	32.9486
	Worst-case	51.4903	43.9562	59.6698

Table 3. Results of demonstrations under ideal conditions and in the worst-case scenario

As a final case, the model was run for the operational situation of Ship B. The fire drill was conducted onboard a bulk carrier, while the vessel was sailing towards Richards Bay, South Africa. All crew members participated in the fire drill, except the watch keepers. Considering the exercise scenario, the following generic factors had effect in this case: insufficient firefighting training and practice, insufficient physical capability (age, weight): 1 crew member over 55 years of age, insufficient supervisor experience: 3 months, external factors (unfavourable weather/sea conditions: NW 6/5).

The model was tested by entering the generic factors into the Arena program and run to estimate vessel drill duration irrespective of drill duration results obtained from the vessels. Other factors were not taken into consideration since they would not affect drill duration. This step was conducted separately for Ship A and Ship B in Arena. Finally, the operational survey results obtained from Ship A and Ship B were noted.

Interval	Ideal Conditions Average	Ship A Average	Ship B Average	Worst Case Average
Process 1	0.7595	0.9240	0.9048	1.2809
Process 2	2.8353	3.3167	3.0864	5.3716
Process 3	3.8118	3.0860	3.0675	5.8228
Process 4	7.2715	7.5800	7.7467	13.0169
Process 5	7.6826	8.8814	8.8949	15.3235
Process 6	6.1255	6.6008	6.5456	10.7228
Process 7	7.1581	9.4328	9.2862	15.2845
Process 8	5.4762	7.0314	6.8293	11.6574
Process 9	5.9808	6.9645	7.2021	11.9716
Process 10	21.1631	22.4639	22.6546	38.8127
Process 11	11.7893	14.8745	15.3808	26.2537
Process 12	27.4723	29.9965	28.1294	51.4903

Table 4. Comparisons of the results in four different cases

3.6. Proposed improvements

As discussed in the previous section, while the overall drill duration was 27.47 minutes, it lasted up to 51.49 minutes under the influence of all the generic factors. This duration (51.49 minutes) is a clear sign of failure during a real firefighting situation on board. In order to minimize and avoid the effect of all generic factors, we proposed actions for each factor identified which are given in **Table 5**.

Factor	Suggested Actions
F1	Toolbox meeting and briefing Emergency response matrix for each type of fire for each designated place Define the response route
F2	Advanced shore-based training and exam Advanced training and exam on board
F3	Combine drills with trainings, teach and demonstrate before use
F4	Identify stand-ins for crew members Change duties in the muster list regularly and switch crew member positions and duties
F5	Identify stand-ins for the supervisor Change duties in the muster list regularly (switch positions and duties) for the supervisor
F6	Crew matrix for same ship types, like the officer's matrix, should be determined
F7	Combined Master and C/O experience shall be minimum 3 years at sea with that rank
F8	Drill evaluation following the completion of previous drills Define and apply best practices and lessons learned from previous drills Identify response target and define goals for crew members
F9	Adjust heading for wind and swell direction Collect weather information to establish a course to avoid bad weather conditions
F10	More specific muster lists More specific listed crew emergency duty placard ready to use in emergency
F11	Defining safe behaviour to eliminate confusion in chaotic situations Company publishing safety campaigns
F12	No overtime for non-emergency use Extra watch keepers for vessels with short routes
F13	Stress effort test before each vessel attendance Age span below 55
F14	Enhanced check-up before each vessel attendance
F15	No alcohol policy Unannounced internal and external drug and alcohol tests
F16	Retention rate should be increased
F17	Spare critical equipment should be supplied
F18-19-20	Equipment cross checking by different persons Checks should be performed against an approved fire control plan

Table 5. Recommended actions

By performing the suggested actions, ship operators can minimize the effects of these factors during operational firefighting drills and real fires. These actions have been entered in the Arena software in DECIDE modules. When the actions identified were taken, the effect of the generic factors was negligible. The layout of the restructured model with suggested actions is shown in **Figure 4**.

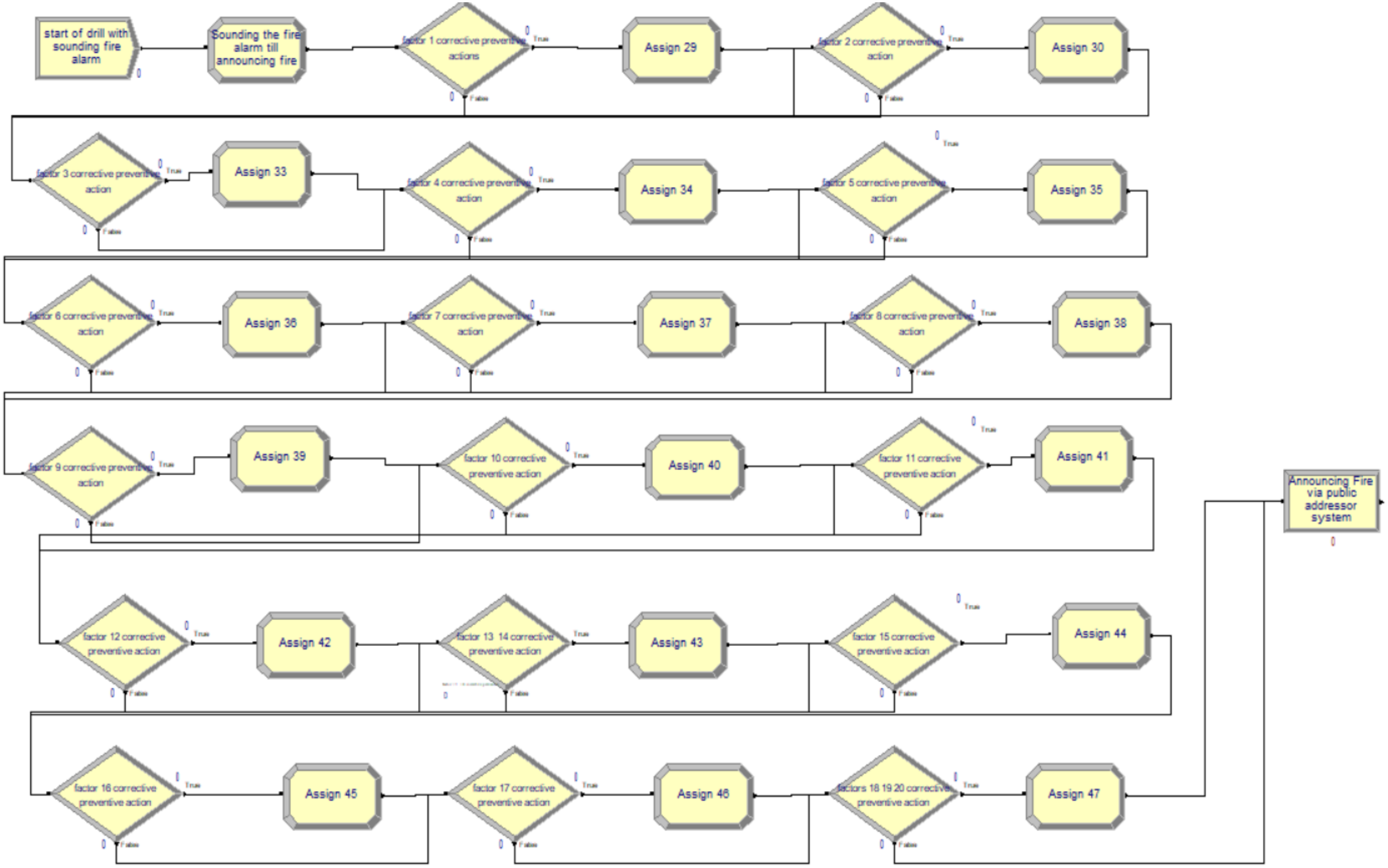

Figure 4. Restructured model with recommended actions

4. CONCLUSION AND DISCUSSION

Ship management companies identify potential emergency shipboard situations to respond to various emergency cases such as structural failure, heavy weather damage, main propulsion failure, steering gear failure, electrical power failure, collision, grounding, cargo shifting, oil spillage, flooding, fire, explosion, abandoning ship, man over board, search and rescue operations, rescue from enclosed spaces, etc. In the context of the safety management system, shore-based managers and shipboard crewmembers should be capable of responding to hazards, accidents and emergency situations at any time.

This paper focused on predicting the level of emergency preparedness on-board ships. The FD-DES hybrid approach was adopted to conduct shipboard situational analysis in firefighting drills. The analysis addressed F3 (insufficient firefighting training and practice) and F4 (missing crew member) as significant causal factors. F11 (lack of safety culture and discipline about the use of personal protective/firefighting equipment and firefighting) and F15 (being under the influence of alcohol and/or drugs) were observed to have a major effect on firefighting drill steps.

The model was then illustrated by running Case #1 (ideal conditions), Case #2 (worst case scenario), Case #3 (Ship A) and, Case #4 (Ship B). The results obtained for four different cases and associated recommended actions were compared. The simulation model was then reconstructed by incorporating recommended actions. The proposed model is useful for shore-based managers as it allows them to improve compliance with the emergency management requirements of ISM Code, TMSA, SIRE 2.0, CDI, etc. Further research is planned to incorporate the statistical findings from audit/inspection reports into drill simulations to continuously monitor ship emergency preparedness levels.

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CONFLICT OF INTEREST

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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