Development of a Robust Framework for Evacuation in Maritime Vessels

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Abstract

For evacuation planning, predicting safe and prompt evacuations are a risky undertaking for commercial or naval ships. When people are concentrated in any one place and movement occurs under duress, factors appear associated with people's patterns of behaviour and lack of situation awareness. This creates uncertainty in many respects. Despite substantial efforts in ship evacuation studies, evacuation prediction cannot replicate specific emergencies as too many variables change dynamically, and human behaviour is a significant variable which is difficult to simulate. Evacuation prediction is at the heart of personnel safety, getting this wrong results in deaths at sea.

Despite significant advances in sophisticated prediction tools, no simple, robust, and efficient frameworks and prediction algorithms exist that can support real time personnel emergency location systems, similarly for design and safety compliance of ships during acquisition or in-service operations.

The challenge is to supply an alternative view to evacuation modelling. Prediction has become too prescriptive and too linear that needs significant effort and resources, and is complex needing extensive and complex tools. By contrast, to bypass elaborate modelling and tools, the International Maritime Organisation's (IMO's) safety guidelines based on several scenarios, present a standard modelling technique for evacuation prediction that uses safety factors to overcome uncertainty. This technique, adopted by the Maritime Industry, is the accepted and plausible approach to characterise performance. The IMO technique is quasi-prescriptive and neglects the uncertainties associated with the dynamics of evacuation and is laborious.

A robust evacuation tool for predicting safe evacuation paths is needed that in part, overcomes some of the issues. In the case of actual emergencies, real time monitoring requires prediction capability with real time interaction with evacuees. This cuts the need to model human behaviour and uncertainties, however path guidance is still needed. For design or in-service planning, behaviours, and situation awareness require modelling, and stochastic techniques are employed to measure the level of safety risk.

The solution relies on the use of network theory to optimise safe evacuation using linear programming techniques. This solution employs ships data and topology, personnel number, path characteristics and uses path constraints to predict and optimise evacuation paths in

minimal computer execution time. The next step is to simulate a ship evacuation time. The simulation calculates the shortest route to the nearest safe point (or muster station) and calculates passenger delay times via the use of hydraulic theory for people movement. Uncertainty is a critical metric and is introduced by using probability theory and Monte Carlo techniques to capture movement data across a wide range of people gender, capability, and age. A case study is presented confirming this approach is possible as a reliable, correct, and robust basis for prediction. The case study is implemented in MS Excel.

Validation of the case study is undertaken by comparing the developed solution against an example IMO evacuation analysis for a vehicle Roll-On/Roll-Off ship.

As a Systems Engineering technique, it can be used for trade-off studies to finalise ship layout design and find path traffic choke points. The approach can be developed for design or validation purposes during the in-service operational phases to check ships safety compliance relating to evacuation performance of existing ship configurations. The solution leads to the development of a simple, efficient, and innovative tool. This makes a significant contribution to the science of evacuation planning and safety of life at sea.

Declaration

I declare that this thesis presents work carried out by myself and does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; to the best of my knowledge it does not contain any materials previously published or written by another person except where due reference is made in the text; and all substantive contributions by others to the work presented, including jointly authored publications, is clearly acknowledged.

Vincent Capizzi

Digitally signed by Vincent Capizzi
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Nomenclature

Item	Description
ABM	Agent Based Modelling
ANEP 77	Allied Naval Engineering Publication 77
ANNs	Artificial Neural Networks
ASET	Available Safe Egress Time
Capable Knowledge	The ability to make use of knowledge to meet an objective
CBR	Case Based Reasoning
DCC	Damage Control Centre
ECT	Emergency Crisis Triangle
Edge	A link that connects nodes in a network
FOM	Figure of Merit
GMDSS	Global Maritime Distress and Safety System
IMIT	Italian Ministry of Infrastructure and Transport
IMO	International Maritime Organisation
ISO/IEC	International Organisation for Standardisation / International Electrotechnical Commission
KPI	Key Performance Indicator
MC	Multi-Commodity
MSC	Maritime Safety Committee of the IMO or the Mediterranean Shipping Company
Navy	Armed vessels in the defence of a nation
NSC	Naval Ship Code
Network	A system of vertices connected by edges
Node	Identified area with physical dimensions such as compartments. corridors, stairs etc.
NodeXL	MS Excel Add-on for plotting networks and deciding metrics

Item	Description
RAN	Royal Australian Navy
RFID	Radio Frequency Identification
Robustness	The ability of the algorithms to consistently find a solution to evacuate people when a solution exists.
RO-RO	Roll On/Roll Off (ships)
RSET	Required Safe Egress Time
RTLS	Real Time Location System
SE	Systems Engineering
SFARP	So Far as Reasonably Practical
SFPE	Society of Fire Protection Engineers
SOLAS	Safety of Life at Sea (IMO)
VHF	Very High Frequency
V&V	Verification and Validation
3D	Three Dimensions

List of Publications

The following publications present research findings originating from this thesis.

Refereed Journal Papers

Capizzi, V. & Marian, R., 2021. A Stochastic Network Approach to Modelling Ship Evacuation. International Journal of Maritime Engineering, Oct-Dec, 163, Part A4(695), pp. A-19 to A-34.

Refereed Conference Papers

Capizzi, V., Marian, R., Campbell, P., 2019. Systems Graphing Algorithm Method for Ship Evacuation Studies, Sydney Australia, International Maritime Conference, 2019.

Capizzi, V. & Marian, R., Campbell, P., 2020, Ship Evacuation and Systems Engineering. Brisbane, (SESA), Systems Engineering Society of Australia.

Chapter 1 Introduction To Ship Evacuation

1.1 Introduction

This research aims to contribute to increasing safety in maritime vessels by developing a framework that facilitates assessment and refinement of methods used to direct and predict safe evacuation during emergencies. The topic of safe evacuation has been of concern to the maritime industry since the inauguration of the International Maritime Organisation (IMO) in the early 1900's, instigated by the sinking of both the *Titanic* in 1912 and the *Lusitania* in 1915.

This chapter introduces the subject of ship evacuation and its corresponding elements that define the research problem.

1.2 History of Maritime Evacuations and Emerging Issues

The topic of formal ship safety in the 20th century came into prominence with the sinking of the *Titanic* in 1912. This event became a catalyst for the adoption in 1914, of the first International Convention for the Safety of Life at Sea (SOLAS). This sinking and then the subsequent sinking of the *Lusitania* were instrumental in defining lessons for future design of vessels and the science of ship safety (IMO, 1974).

More than 1500 passengers and crew died, and the *Titanic* disaster raised questions about the safety standards in force at the time (Commander Richard R. Paton, Oct 2017). The substantial loss of 68% of the people onboard came as a great shock because the vessel was equipped with the most advanced safety technology at that time, had an experienced crew, and was designed to be 'unsinkable' (Frey, Savage, & Torgler, 2011). Only 711 of the 2,222 people onboard survived. Lifesaving lifeboat appliances had a capacity of saving 1178 passengers or 53.5% of the loaded number of persons onboard. Reports suggest that during the 2-hour 40-minute ordeal, deck officers made the lifeboat shortage matters worse by launching lifeboats that were partially empty. The predominant behavioural issue reported showed that passengers on the Titanic remained calm and behaved in an orderly fashion prior to the sinking event (Irish Central, 2021). The major factor was the long time over which the disaster unfolded. This time was abetted by the social structure at the time, for example, 'saving women and children first'. However,

467 more people could have been saved with proper instructions and communications, less confusion and in some cases, avoiding pockets of isolated panic. This sinking appears to imply that the time to evacuate personnel was/is not the governing factor in this type of disaster.

Three years later, the passenger liner Lusitania was struck by a German U-boat torpedo which cost the lives of 1313 persons out of 1960 crew and passengers (67%) (Wang R.-H. J., 2022). On the Lusitania, selfish behaviour prevailed, in contrast to the Titanic event where the adherence to social norms and social status dominated. This difference could be attributed to the fact that the Lusitania sank in only 18 minutes! The brief time available created an instinctive urgency for self-preservation producing an environment where instinctive or impulsive behaviour dominated.

On 13 January 2012 –100 years after the *Titanic* sinking – the *Costa Concordia* was navigating in the Mediterranean Sea (the Tyrrhenian Sea) along the Italian coastline. It had 4229 persons on board (3206 passengers and 1023 crew members), sailing in favourable meteorological marine conditions. At 21:45 (local time) the ship suddenly collided with the 'Scole Rocks' at Giglio Island. The ship had just left the port of Civitavecchia and was heading for Savona (Italy) (Italian Ministry of Infrastructure and Transport, January 13 2012). The accident was due to a combination of factors such as irreversible flooding, the ship heeling more than 30 degrees, the loss of propulsion and associated ancillary services, and the disorientation by crew members. The incident occurred at night. It was an unexpected outcome of poor seamanship. The Ministry of Infrastructure and Transport (IMIT) cited that associated poor emergency management and entrapment with open sea vessel incursion were main issues. The evacuation of the *Costa Concordia* took over six hours, and of the 4229 people known to have been aboard, 32 died onboard with a further 157 people injured (IMIT, (Costa Concordia Report on the safety technical investigation, January 13 2012).

The following specific evacuation perspectives were documented by IMIT.

1 Timing – the evacuees would have gained precious time to reach the muster stations, should the abandon ship be given appropriately. Lifeboats would have been launched 36 minutes after the general emergency signal, which was adequate time to gather all persons in the spacious and suitable muster stations.

2 Time & Communications – the Designated Person Ashore never thought to speed up the Master plan to abandon ship
3 Awareness – failure in terms of emergency handling was characterised by the lack of alertness
4 All died due to the delay of beginning the onboard emergency procedures
5 None of the crew members called the roll (or tried to) or registered the number of the passengers as they went on board to the lifesaving equipment.

Time was a significant element contributing to this tragedy, together with the ensuring chaos, emergency awareness, passenger whereabouts and the combination of physical circumstances (flooding, ship heel, fire, and blackout). With the ship having the latest safety emergency system and with procedures and tools/lifeboats in place, IMIT concluded that uncertainty, confusion, lack of situation awareness and communications (or lack thereof) were significant contributors in the loss of life.

One clear differences between the first two events were the state of war at the time of the Lusitania sinking (Frey, Savage, & Torgler, 2011) where ocean ship liners were targets exhibiting levels of unpreparedness under wartime conditions.

The above examples share designs that have become standard for ocean liners, all three ships had safety requirements built into the ship's capability. However, if one includes the designs related to Navy vessels, that is not the case. Navy vessels have smaller spaces, complicated routing, specific deck movement structures such as ladders, etc. These make evacuation prediction more complex. Also, other ships have their own specific deck layouts, for example cargo ships, most space is allocated to carrying cargo, or for that matter, other types such as ferries can carry passengers, cargo or cars simultaneously or separately. Ship types strongly influence ship layout architecture.

Better emergency strategies are needed to augment safety. The above examples implies an assumption, that for safe evacuation, evacuation time is not the primary discriminator for safety. The examples show that other factors exist that have a strong implication to safety. Other factors, uncertain in nature, may include situation awareness, communications, leadership, person location, route familiarity and emergency directions form a vital part in the safety in numbers in confined spaces. (Team, 2020).

The history of maritime disasters is littered with situations that are different and uncertain. Evacuation prediction conflicts with the accepted principle that time is most critical in these circumstances. (See Chapter 4 for further assessment of this issue). There is a need for other factors need to be considered for conducting evacuation prediction.

1.3 Research Motivation

For centuries, complex systems have been handled by breaking the system into smaller components, examining, and analysing each event/component/subsystem in isolation, and then combining the results in order to understand the behaviour of the components, (Leveson & Thomas, 2018). These components are assumed to interact in direct and known ways. Behaviour has also been handled in the same way.

However, events such as ship sinkings create "unknowns" that cannot be found by breaking the system behaviour into chains of events. Another phenomenon known as emergent behaviour occurs which is a result of component interactions, and not individual components outputs.

Current prediction tools for evacuation that are based on deterministic calculations using evacuation time as the governing and key factor in an evacuation performance framework (IMO, 2016). This thesis challenges this idea by advancing the concept that evacuation time is not the single most unique factor to decide evacuation efficacy. It re-emphasises attention on how to find other related factors to better define evacuation, in this case how interactions play a part. Accidents can occur due to unsafe interactions among components that have not failed.

To help the understanding, this research examines known practices based on the threads discussed above. It does this by conducting reasoned assessment of available evidence, applying technical constraints, reviewing current evacuation methodologies, assessing historical knowledge and applying decision-making capability. For ship design, a new paradigm can be used in the design of ships to capture ship evacuation performance. In the case of ships already in operation, an alternative method would consider the use of real time person location data to provide a significant increase in ship safety by taking out the evacuation time variable.

The research aims to focus on the maritime ship context to account for the regimen and the complexity of Navy (military) ship design. Navy ships have more varied spaces,

physical space constraints, complexity in the use of space and a crew which operates in a difficult environment. However, technical data for naval ships is limited, and the use of commercial ship data sourced from ferries, cargo ships and passenger liners, make it easier to aid this research, including discussions surrounding this area. Note that evacuation in commercial ships can be considered to be more challenging than in naval ships, where naval ship personnel have significantly increased levels of special and continuous training.

1.4 The Research Problem

The research problem this thesis solves is:

Can a evacuation prediction path method be developed to overcome the current prediction modelling deficiencies and do it an economical and efficient way.

The path prediction problem is an instigator of a move towards overhauling the traditional approach. Path prediction has the effect that all the elements mentioned previously have been considered.

To address this research problem the following subproblems need to be investigated and resolved:

1 Investigating the state of the art in evacuation prediction modelling and assessing an alternative approach
2 Investigating interaction approaches, normally used in the communications and IT fields, to model physical architecture
3 Assessing the modelling of ships architecture and people flow
4 Investigating mathematical theory to aid architecture solutions and relating this to emergent behaviour.
5 Investigating Monte Carlo techniques to solve the uncertain stochastic aspects to path choice based on probable outcomes.

The research hypothesis for this research is:

Simple and correct evacuation prediction can be developed, that solves the space/time/interaction problem and furthermore, can be used in the design of ships and also can be used in real time to aid evacuation.

The development of a simplified prediction method is an added capability to the maritime industry and current methods.

1.5 Improvements to Maritime Safety

One of the consequences of the *Titanic* sinking in 1912 was the adoption, two years later, of the first International Convention for the Safety of Life at Sea (the SOLAS Convention) in the UK. The main aims of SOLAS were to specify minimum standards for the construction, equipment and operation of ships, compatible with the safety of personnel. The 1914 version of the Convention was gradually superseded, respectively by SOLAS 1929, SOLAS 1948, SOLAS 1960, and SOLAS 1974. SOLAS 1974 is still in operation today, amended and updated many times (IMO, 2020).

During this period, a conference convened by the United Nations in Geneva in 1948 eventually led to the establishment of the International Maritime Organisation (IMO), a body responsible for the safety and security of shipping and the prevention of marine pollution by ships by adopting SOLAS guidelines. These guidelines include evacuation performance assessment criteria to enhance safety of life, as articulated in the IMO's Maritime Safety Committee Circular, MSC.1/Circ. 1533, 6 June 2016 (IMO, 2016), MSC 1533 . As part of the IMO's '*raison d'être*', emergency evacuation simulation now plays an important part in the consideration of design of ships as well as vehicles, aircraft or buildings, with interest coming from academia, and industrial and scientific fields (DiNenno, 2002).

1.6 Discriminating Factors for Ship Evacuation Prediction

Commercial and Navy vessels (armed vessels in the defence of a nation) have important differences. Data on commercial shipping is prevalent, under the auspices of the IMO. By contrast, Navy data is much scarcer, given the specific nature of Naval security operations.

Navy personnel are trained in escape and firefighting drills, and they tend to be fit, alert and proactive. Onboard training is one main area where the design of the whole ship system can influence escape and evacuation (NATO, 2017). The other main area for the design is in the Ship's General Arrangement (Carnie & Hicks, 1 July 2000), (Bellas, et al., 2020).

The main discriminators are passenger capability, ability and behaviour (in the presence of any specialised training and ship layout awareness). The following sections detail aspects that are considered important for safe evacuation of a vessel in emergency and the actual complexities of evacuation and evacuation planning.

1.6.1 Causal Circumstances

It is clear that the causes of an accident play an important aspect to determining what disasters unfold. It encompasses systemic factors which contribute to disasters. The causes affect the evacuation outcomes. Current prediction schemes do not do that.

1.6.2 Situational Awareness

Given the fit for service crew onboard, a major driver for safe evacuation is situation awareness which implies the judgement and knowledge about:

6 What is the state of the emergency?
7 Where is the emergency?
8 What is being done?
9 Where are the resources?
10 Which route is the safest to escape?
11 What is perceived as a future course of action?
12 What does one do to preserve life?

Situation awareness increases safety and efficiency of actions of individual crew members and the crew as a whole and relies on a person's perception and understanding of their dynamic environment. This understanding involves perceptions of dynamic elements in the current situation, comprehension of the current situation, perception of future status and finally, decision making and requisite actions (Wright, Taekman, & Endsley, 2004).

Situation awareness significantly reduces evacuation time through a combination of location awareness, decision-making capability, and the preparedness to escape. Overall, situation awareness reduces the psychological pressure of the evacuee and the level of uncertainty of the evacuation process. It increases the confidence of the evacuee and drastically increases the likelihood of a positive outcome of the process.

1.6.3 General Arrangement of a Particular Ship

The general arrangement of a particular ship has many characteristics that influence egress in the actual emergency. These characteristics include:

1 Levels of lighting
2 Passage and stairways dimensions and designs – the angles and handrail designs are particularly important to effect quick transits
3 The proximity to the Muster Station
4 The size and placement of hatches and watertight bulkheads
5 The identification, placement, and number of firefighting appliances
6 Stair dimensions and access
7 The impact of using life jackets and safety appliances
8 The size and number of separate compartments
9 The placement of fire curtains
10 The quantity and location of response equipment and resources
11 The storage location of combustible materials and ammunitions
12 Ship trim with associated rolling and pitching frequencies
13 Number of crew.

As discussed previously for Navy ships, spatial arrangement and use present challenges when encountered with forced evacuation (Carnie & Hicks, 2000). The combination of targeted design, training, and situation awareness learning impacts evacuation performance.

1.6.4 Physical situation of evacuation

Evacuees must decide, in an emergency situation and while under stress, their options for evacuation. The physical situation is specific to each case, and the environment can be any combination of the following:

1 The ship is under motion – as it pitches, heels and yaws – and its effect on mustering timing (Wang, Loughney, Yang, Wang, & Wang, 2021).
2 The ship is subject to the prevailing dynamic conditions of the sea, increasing sea states exhibiting increased wave impact and water dispersion environments also affecting flight time

3 The levels of smoke and gas toxicity affecting egress and movement speed
4 The density of human traffic in any particular section of the ship affects which particular route is taken and the timeliness of identifying optimum paths
5 The number of obstructions, either as a fixture or as debris, furniture dislocation, flooding affecting movement speed
6 A An individual's predisposition based on their immediate local experience can influence which alternative exits are taken
7 The individual's conditioned response (human behaviour) as a result of crew training without overall emergency situational status (could hinder or better the situation)
8 The traffic level interaction with obstacles affecting the individual's speed of egress and introduction of delays
9 The organisation of the ship's staff affected by organisational relationships and sailor hierarchy, roles, and authority
10 The direction by command to respond to operational situations and collateral hazards, affecting decision making and ultimately, egress time (Carnie & Hicks, 2000).

Disaster simulations of a Navy ship during an emergency are considered uncertain and risky and, with current evacuation deterministic prediction methods, do not represent real events and do not capture the factors listed above. Moreover, due to the variability of events and the uncertainty of potential simulations, they are not that representative of an actual disaster and associated evacuation episode.

Many techniques are available for designers and operators to simulate evacuation prediction. However, they suffer problems of data availability, data complexity, data relativity, intensive resource requirements, uncertainties, and computer processing limits.

1.6.5 Human Behavior that Influences Evacuations

In commercial ships, characteristics of disaster/evacuation situations indicate common elements which show that evacuees at the moment of evacuation are exhausted (50% estimated), drunk or at least tipsy (30%), and disoriented (20%) (Vorst, 2010). Vorst argues a pattern appearing with the following features:

1 Most people (50% or more) are unable to make adequate risk estimations in typical evacuation situations, due to lack of training, alcohol, and stress

2 Most people are not inclined to evacuate which causes delayed evacuation and more casualties

3 Most people are unable to make adequate decisions in new problem situations, due to anxiety and alcohol and stress

4 Most people are unable to communicate (speaking and listening) unambiguously and clearly, due to alcohol and stress

5 Most people tend to focus their attention poignantly (like tunnel vision), due to alcohol and stress. They do not have the overall picture of new situations needed for best adaptive behaviour.

6 Most people tend to behave as they do normally. They choose well-known behaviours or copy behaviours from others near them.

7 Most people have lowered thresholds of emotional behaviour due to alcohol and stress. They are easily triggered to be angry, anxious, or aggressive.

8 Most people are unable to control and smoothly perform motor activities due to alcohol and stress. They are prone to accidents.

9 A percentage of people find it difficult to make (Schmidt, Richev, Zyolensky, & Maner, 2008) fight or flight decisions. Perceptions of immobility in the context of the challenge were reported in 13% of Schmidt et al.'s sample, compared with a 20% reporting a significant desire to flee. Conversely, in a fire emergency, the common expectation is the assumption is that occupants panic. The possibility of panic in a fire has been considered a 'myth' by social scientists since the 1970s, although the media use this concept for its drama and sensational connotation, but there is little evidence of panic in actual fire situations. It is a widespread misconception to believe that people caught in a fire will panic and try to flee in a stampede (Society of Fire Protection Engineers, 2019).

10 In a commercial ship, language and cultural barriers may add to the evacuee's confusion, affecting situation awareness. Many studies (Safety4Sea Editorial Team, 2022) have shown that the impact of language and culture on human failures at sea; the lack of a common language makes a ship a high-risk working environment.

This situation is worsened by the lack of the means to decide a person's whereabouts, the specific environment of the location and the lack of communication to move to a safe space.

Implementing real time monitoring of crew movements does not complete the scenario; there must be a system that monitors the environment, to provide aid to escapees to negotiate alternative options for escape. If evacuee movement is tracked, it does show a person's specific and local environmental condition. This is where path prediction can add to capability and enhance direction finding, route choice, enhance communication, and infer the environment. This approach will have a significant advantage over the status quo.

1.7 Specific Issues to Consider when Designing a Ship Evacuation System

Current evacuation prediction methods do not supply evacuation solutions but rely on standard scenarios in which deterministic theory provides a possible performance outcome against a time standard, which is not related to the actual emergencies (see Chapter 2 for details about the state of evacuation modelling), particularly for Navy ships. Here is where causal factors are important, and architecture should account for interactions and emergent behaviour issues. Think of the architecture as a network which causes emergent passenger behaviour to develop! For example, if a space plays a central role to the ship, passengers will tend to move in that direction; if a corridor is accessed by a ladder, then passengers may tend to a avoid this route.

Navy ships are complex due to the number and compounding of topological and environmental issues and their connections that challenges the evacuee when trying to evacuate when confronted with inflicted damage or personal harm. These complex issues limit the efficient and economic means of evacuation prediction. The prediction problem is an uncertain environment, but can be characterised by checking the following criteria assessed during the research:

1 What is the best ship layout to ensure maximum safety to onboard personnel?

2 How long does it take to evacuate a ship in an emergency?

3 During an emergency, which path should one take?

4 Does the selected path go around the area of concern, such as flooding, smoke, fire, or toxic gas areas?

5 Are traffic delays affecting the evacuation routes?

6 During an emergency, there are many unknowns and unstable states. How does one take these into account?

7 Is human behaviour included in the prediction?

8 Does the analysis account for variabilities in the velocity of a person's gait or speed?

9 Can the simulation be used in a real time environment?

10 Does the simulation include all ship types?

11 How does one test that the simulation supplies to a realistic solution?

12 Are congestion points along the route open to calculation and can something be worked out to improve the spatial constraints?

13 Does the simulation account for environmental factors like smoke, toxic gases, and lighting levels?

14 Does the simulation account for human traffic?

Currently, these issues cannot be investigated using traditional deterministic tools.

Emergency evacuation prediction cannot be prescriptive as dynamic circumstances occur to limit usefulness; such limitations include obstructions, fire and smoke, gas, poor lighting, uncomfortable temperatures, flooding, and ship motion. These circumstances play an important part in how a person reacts. While data on evacuations from ships, buildings and aircraft is abundant, none of the data sets can be used to precisely predict safe performance. Thus, this research uses an alternative (causal) performance framework approach to specify common attributes to ensure uniformity of application. In this situation, typical causal benchmark scenarios are proposed and relevant data should be specified to decide performance to quasi predict actual emergencies. This approach is a reasonable first step to understand the problem space, and what has been conducted beforehand.

Above all, these criteria add to the uncertainty of the evacuation simulation.

1.8 Reasons for Conducting this Research

The driver for this research is the recognition that by assessing the factors listed above, a better evacuation framework can investigated and found which is simple and efficient to support real time monitoring or to predict evacuation prediction. The state of the art (as documented in Chapter 2) supports the research to provide an alternative to current tools that represent a simple, fast, and reasonable approach that overcomes the uncertainties in evacuation. A part of this overall thinking, the solution for a better path selection method underpins the alternative prediction method.

In all cases, the focus is on implementing onboard real time personnel location systems to reduce the number of deaths. This drives the efficiency/execution requirement which has a flow on effect to evacuation planning in the support of the design of ships.

The efficiency and executive requirements must address information clarity and direction to evacuees during an emergency. This requirement is local and dynamic, with knowledge supplied related to potential evacuation paths, potential obstacles and local environmental conditions, including information to increase situation awareness to aid to the passengers and crew. A positive outcome in the design of ships is to provide evacuees with clear and correct escape information in-situ to guide decisions a priori. For this to happen, if prediction is linked to real time conditions, then it supplies the means to acquire local awareness of what is happening in the environment. Such a capability overcomes the limitations of current approaches and supplies essential situation awareness information to evacuees to make informed decisions about safety.

A ship's lifecycle is categorised simply into typical phases such as the ship acquisition phase (design, procure and test), the operational (termed in-service) phase (conducting operations or missions and sustainment) and the disposal phase. During acquisition or in-service phases, a prediction can be put to good use across all the phases supplying positive safety benefits for individual and specific purposes.

Safety plays an important part in the lifecycle of a ship platform. It informs safety efficacy related to system requirements, design, operations, and the environment. As such, reasons for pursuing the research are as follows:

1 To develop a unique and simplified tool to predict safe evacuation from ships accurately which overcomes the limitations stated above in uncertain circumstances

2 To overcome the limitations of personnel number and location uncertainties in ship emergency situations which cannot be supported by deterministic approaches

3 To find a more realistic approach that supports real time evacuation data and the design of ships

4 To use prediction as a means to investigate methods that reduce the complexity of evacuation decision making

5 To assess ship disasters that have supplied evidence and information that can aid the achievement of being safe after an untenable emergency incident has occurred

6 To re-evaluate evacuation time to achieve as an acceptable safety outcome. However, ship history suggests that the amount of time to sink a ship does not correlate to the numbers of casualties (see Figure 4.1).

7 To further explore evacuation/egress time influence on evacuation which directly relates the certainties–uncertainties in emergencies.

Planning becomes complex if one accounts for the many variables that need to be considered if one is to simulate the problem accurately using a prescriptive method. However, in real time emergencies, most of these variables become insignificant if real time location monitoring is complemented with optimisation. This approach is a novel and significant aid to maritime and naval safety. Better evacuation decision-making capability will simply and efficiently overcome the limitations of current deterministic and complex prediction approaches.

1.9 Significance of the Research

This research is significant because it aims to simplify and make efficient evacuation prediction that can be employed to underpin both real time personnel location data with path optimisation and planning purposes to aid decision making. This tool can be used in the design of ships to enhance safety outcomes on Maritime (Commercial and Navy) vessels during emergencies. This increases its safety benefits in a positive way.

Evacuation analysis provides crew and passengers with the best possible tools for escaping the ship safely, aiming to do so in a calm manner. Human behaviour in these situations is especially important because it not only helps avoid undesirable events, disorganisation, and panic, but is of utmost importance to personnel safety. That is only achievable if crews and passengers have inherently in place, a safe design, a safety

warning system, and an information system to inform evacuees by communication by guidance to make informed decisions to advance safety of life and opportunities. This increases the confidence in the safety of maritime operations, following policies and regulations for safety of life at sea.

1.10 Scope of the Research

In developing a simplified, efficient evacuation path prediction technique, it simply adds to safety of personnel. Any incremental advancement to aid safety of life is intrinsically beneficial to maritime operations.

The research does not aim to develop a full simulation model that is realistic of emergency situations, such as conditions of fire, flooding, or capsizing.

The evacuation scope for this research includes:

1 Development of the time needed to evacuate from one area of the ship to the final destination. Does no include the time to respond to the alarm.

2 To consider the full availability of escape arrangements, unless otherwise stated

3 To consider evacuee flow to move from the source (compartments) to the sink (muster station) with counterflows considered simplistically

4 To include the modelling the ships compartment/space topology

5 To apply stochastic techniques to frame evacuation performance in an uncertain situation and to decide movement performance based on probabilities and published data

6 To include the dispersion of ship's personnel throughout the ship

7 To calculate personnel flows and their physical properties relating to their ability to negotiate movement velocity

8 To using visualisation tools that supply an understanding of the personnel and topology dynamics

9 To model a documented ship layout based on IMO guidelines

10 To assume personnel behaviour movement is reflected on traffic and movement velocity.

Human behaviour considerations such as that found in group situations or families is outside the scope of this research. The research does not include considerations of ship motion, ship heel and trim.

1.11 Contributions of the Research

The following description underpins the work undertaken in this research field. The current research is based on using a novel graph theory and linear programming approach to solving the best path for evacuee evacuation.

Technical data is primarily sourced from Industry (instead of real time data) to confirm the basis of this approach. Used in conjunction with a combination of proven linear programming techniques, the approach can be optimised to decide escape routes.

The approach also uses Monte Carlo simulation to find the uncertainties in the evacuation solutions. Monte Carlo simulation is a risk evaluation technique whereby one iterates results by substituting a range of values by a probability distribution for any parameter that has inherent uncertainty, in the case of this analysis, the individuals' velocity and inherent time of movement. It then calculates results over and over, each time using a different set of random values from probability functions (Kroese, Taimre, & Botev, 2013). Use of Monte Carlo simulation is the major difference to most of the well-known software tools on the market today.

1.12 Thesis Structure

The thesis is structured as follows:

Chapter 1, as the introductory chapter, supplies a brief introduction of two significant maritime disasters that have involved evacuations that have subsequently shaped the course of evacuation planning. It finds the conflict between evacuation time and a safe outcome. The research problem is to challenge the judgement that evacuation time is the highest critical factor in evacuation prediction. To support this, common factors that should be considered in investigating a better solution when planning evacuation is presented.

Chapter 2 provides a critical overview of the research questions and current processes to characterise the purpose of the research and propose possible means to overcome deficiencies in current evacuation planning approaches.

Chapter 3 reviews the methods that have been used to date to simulate evacuation, finding possible method alternatives not directly related to evacuation but used in this research.

Chapter 4 further explores instances in history that affect the thinking behind the approach to solve the research problem and explores issues to consider.

Chapter 5 presents the development of an evacuation framework that further examine the means to develop the solution of the research problem.

Chapter 6 presents qualitative evidence that verifies and confirms the evacuation simulation development to supply a consistent application for the prediction of evacuation.

Chapter 7 presents a case study that explains the use and processes involved in the evacuation prediction and presents a case for verification and validation of the prediction method.

Chapter 8 presents the stochastic process and Monte Carlo assessment. It discusses how the techniques supply a risk-based data instance to mitigate uncertainties in the evacuation prediction approach.

Chapter 9 supplies detailed information about Real Time Location systems and how the prediction can be used to augment the monitoring system.

Chapter 10 presents the conclusion of the research and supplies recommendations for future work.

1.13 Concluding Remarks

This Chapter discusses the historical cases of the sinking of the SS Titanic, the Lusitania, and the Costa Concordia. It has identified a conflict in the convention of conducting evacuation planning. This conflict refers to the current thought that the sole discriminator in evacuation prediction is evacuation time. Factors are introduced that help to understand

and highlight the issue which is both complex and dynamic and related to the environment and causes that ships must manage during emergencies. This conflict or knowledge gap arises from both internal and external influences and can be expressed as uncertainties. To mitigate the conflict, evacuation planning tools that consider the added factors are needed.

This knowledge gap specifically refers to the impact of current escape path prediction methodologies which are complex, lack efficiency, require specialised resources and are costly to implement, see Chapter 2. This issue sets the context for the research problem, namely, to develop a simple, robust, and efficient algorithm and framework that can be used to implement a real time personnel location system for onboard commercial and navy ships, and for use in evacuation planning.

The research also contributes significantly to the current state of evacuation planning. The contribution relates to the core issues of tools predicting evacuation times with due consideration of the emergency dynamics concerning situation awareness and preparedness. Safety is also considering the assessments that are simpler and more robust to argue the safety risk. The prediction approach that allows the means to conduct extensive, wide ranging and plentiful planning activities leads to safety and subsequent fewer deaths at sea. It is a requirement that a method needs to be able to conduct iteration to be able to conduct optimisation and comment, which drives the necessity for computational speed.

The next chapter presents a thorough and critical assessment of the state of the art in evacuation prediction approaches, highlighting the research gap.

The approach to solve the problem and the algorithms developed as part of this research were presented during the International Maritime Conference in Sydney in Australia in 2019. These algorithms were of interest to the Royal Australian Navy (RAN) Technical Bureau. It is expected that an application of this research will be further developed to conduct platform stability (flooding) as well as evacuation assessments of Navy ships in the pursuit of end-to-end survivability prediction studies. Real time data monitoring and optimisation is innovative and significant in that this approach has not been applied in the Navy context.

Chapter 2 State of the Art in Ship Evacuation Prediction

2.1 Introduction

Chapter 1 identified a knowledge gap on the ability of packaged software applications to present better decision-making options to achieve safety quickly and efficiently as an emergency unfolds on maritime ships. Following established techniques of evacuation simulation may not necessarily reduce the risk of casualties.

This Chapter assesses the current methods to substantiate the premise that current methodologies are resource heavy and don't account for factors involved in presenting a more complete picture of evacuation.

The research problem has been demonstrated by the partial sinking in 2012 of the SS Concordia, which happened after almost a century of advances made in the safe operations of ships.

The Chapter assesses the state-of-the-art methods presented in the literature to solving the ship evacuation prediction problem in uncertain circumstances. The chapter goes on to explore alternative opportunities that may support reducing the research gap and further investigate those underlying factors to support the solution of the research problem.

This Chapter also looks the possibility to check evacuees in real time and provide information and advice for evacuees to make decisions in-situ. This view, minus the real time aspects is extended to developing ships designs so that the technique can be used in simulation studies using a multitude of environmental conditions.

Therefore, the safety of evacuation is extended to be used across the lifecycle stages in the life of a ship. In the naval context (Commercial ships have a similar cycle), the stages are identified as such,

1 The Concepts stage: ship architecture is investigated for the of procuring a ship type to meet mission requirements. Concepts are explored and layout plays a very important aspect which relates to ship crew, accommodations, damage control, evacuation control, work centres etc. Relating to safety, prediction tools can be used to supply a preferred architectural concept, including a mission optimised architecture.

2 Risk mitigation and requirement setting in this phase, after concepts have been developed, ship options are investigated. These ship options will be analysed, and a preferred procurement selection option is chosen to minimise risk and optimise safety. Top side and compartment architectural schemes are provided. Requirements are developed. Here a prediction capability is a necessary tool to prioritise the options iaw with architecture and evacuation prediction.

3 Acquisition: this stage is the formal procurement tendering stage, with the client going out to industry to supply a costed choice to meet the mission and support requirements. The client will receive a number of options to be assessed and prioritised. To support this assessment, the use of an architecture and prediction tool would be indispensable to select the preferred procurement choice.

4 In-Service: During in-service operations, as well as sustainment activities being undertaken, the ship will be in a continuous cycle of capability upgrade. The most important aspect is the development of the architecture options to meet the upgrade requirements. This becomes a very important aspect as it affects the ships mode of operations, the systems utility, and the safety of the ship. The use of a ships architectural safe layout will support the final optimisation assessment.

Disposal follows.

The method adopted takes on an additional dimension; its use can be used to examine interactions and emergent behaviours and the same tool can be used to develop a prediction method.

2.2 Primary IMO Directions - Guidelines for Evacuations

The International Convention for the Safety of Life at Sea (SOLAS) Regulation II-2/28-1.3 in 2002 requested that an appointed Sub-Committee on Fire Protection (FP) to develop guidelines on evacuation analysis for passenger ships and high-speed passenger craft. This request endorsed a series of documents detailing guidelines published as circulars, the most important being the Maritime Safety Committee (MSC) Circ.(s) 1033 (2002), 1238 (2007) and currently, MSC.1/Circ. 1533 (2016) (IMO, 2016). Each of the circulars built on upgrading and extending the existing guidelines. MSC.1/Circ. 1533 (2016) is the current accepted minimum standard to conduct evacuation prediction.

Additionally, specific purpose-built evacuation tools developed by Industry and the Academia have been developed around these guidelines.

In accordance with the International Maritime Organisation (IMO) SOLAS guidelines and in particular MSC.1/Circ. 1533 published 6 June 2016 (IMO, 2016), the evacuation prediction as presented in the circular relies on evacuation time performance as the important performance metric to be achieved, in limited scenarios devoid of causes, i.e., night and day.

People in ships, buildings or even underground facilities lack situation awareness and are not trained to make decisions optimally and fast. As detailed in Section §1.5, several added factors were suggested that affect performance including situational awareness, human interaction with the environment, human behaviour, crowding, mental fortitude and training. These factors can undermine evacuation performance, where time may or may not be a crucial factor.

To standardise evacuation performance against a range of ship designs, the Guidelines benchmark scenarios, and relevant data specified to assess the evacuation performance of a particular ship. All the data and parameters given in the guidelines are based on well-documented statistics originating from the civil building industry (Society of Fire Protection Engineers, 2016). These supply performance criteria in terms of total calculated evacuation time and identified as the Required Safe Egress Time (RSET) compared to the Available Safe Egress Time (ASET). ASET is based on experience and history of the ship type (IMO, 2016). The approach to minimise the gap – in other words, ASET minus RSET, and is prescriptive. This is under the control of the user and is conducted by hand calculations to decide the optimum route for evacuation. Uncertainty is not considered, and it is near impossible to conduct route optimisation of alternative paths in an efficient and correct way using applied constraints.

The IMO Guidelines are wide ranging among the current 175 member states. In Australia for example, the Royal Australian Navy (RAN) seaworthiness policy and regulations employs significant focus on the safety and environmental compliance for all the Navy's engineering programs. In the case of Australia's Fleet, the use of Classification Societies for compliance to these objectives use the Prevention of Pollution from Ships (MARPOL) and SOLAS requirements for the build, maintenance and operation of these ships. Classification societies employ IMO/SOLAS guidelines for evacuation safety and is also

employed by the RAN. Therefore, the Guidelines are the standard for modelling evacuation performance.

2.3 Evacuation Supporting Influences in Literature

Fire is the most common and disastrous contributor to lack of safety (Society of Fire Protection Engineers, 2016), and therefore, research mostly covers the evacuation for a multitude of hazards such as fire, smoke, gaseous toxins and reduced lighting, as identified in the building industry. The inclusion of hazards introduced by the sometimes 'mediocre' compartment route design of ships is worsened by the environment, crew numbers, and any damage control and firefighting processes.

Traditional escape and rescue methods have been developed over many years of service but are limited in conducting assessments related to uncertainty and actual emergency dynamics, safe areas/route optimisation, local arrangements, configuration impacts, crew behaviour and limited situational awareness (SFPE Task Group , 2019). Allied research institutions (Natural Hazard Research Australia, 2022), (UNSW, 2022) have conducted research to better understand the impact of situation awareness in the development of evacuation to plans and designs for a safe solution. Escape and eventual rescue in the case of Navy frameworks, rely on best practice and history, supplemented by the vessel's organisation and its disciplined personnel that are fit, organised, and well trained. Personnel have continuously been made aware of procedures and hazards by in-situ training and drills (Carnie & Hicks, 2000). Even with these protocols and procedures in place, disasters still occur onboard Navy ships, confirming that training alone is only one of the mitigation techniques for safety.

No formal evacuation design rules for vessel design exist for safe evacuation. Nevertheless, the MSC.1/Circ. 1533 (IMO, 2016) SOLAS guidelines prescribe a set of parameters used in deterministic calculations which are based on agreed standard scenarios incorporating personnel standards for movement. The guidelines are limited. To add further, the limitations of these guidelines related to developing real time prediction techniques suffer from the following:

1 Specific ship evacuations are not significantly referenced in industry-related evacuation studies with methods and technical data adopted from the same

2 The lack of evacuation performance data because it is specific to each class of ship, including personnel capability, environment, and ship dynamics

3 Limited data on the effects of ship/vessel motion, vessel list, passenger physiological capabilities and restricted visibility. Ship motion is not significant until there is substantial ship listing (> 20º) (Brumley, 2002).

4 Limited data on the effect of media systems. Poor media annunciation systems show a moderate influence on evacuation times when compared with an ideal scenario (Brumley, 2002).

The SOLAS Guidelines prescribe a first systematic step that can be adapted to ship design processes by simulating evacuation by prescription and then by analysing parameters important in characterising escape via the mix of ship configuration and route optimisation. Tailoring the Guidelines in design studies by including uncertainty and other factors probability functions which characterise evacuation time increases the efficacy of evacuation prediction. These important aspects can be examined either during the acquisition or operational phase of the ship's lifecycle.

Appropriate media systems onboard ships add strongly to situation awareness and are a means for supporting both real time and design prediction tracking for personnel providing a significant increase to safety.

2.4 Current and Interesting Approaches in Ship Evacuation

A literature search surveyed the different approaches in simulation evacuation prediction. It covers the aspects to understand the current state of prediction outlining the different methodologies and supplies a comment to their usefulness to meeting the research problem.

The literature on specific, efficient, and simple mathematical optimisation techniques that can be adapted for ship evacuation is limited. A significant research paper taking the same approach as presented in this research is supplied by Ching-Wu et al. (2013). This study presented a graphic search model that is used to simulate different evacuation scenarios using a network nodal flow method coupled with a minimised cost model to decide the shortest path. The modelling has stringent assumptions that limit the outcomes to a purely mathematical exercise. While being viewed as an efficient means to decide paths, the paper provided no discussion on how this modelling is implemented or accomplished, the

tools used, nor how uncertainty is considered and how to implement it as a system to achieve a safety outcome onboard ship during an emergency.

The solution to these limitations lies in the definition how spatial properties are modelled to capture specifics such as topological, geometric, or geographic entities. Modelling techniques require mathematical representations of spatial properties where spaces are represented and spaces relationships ae built up in the approach to define overall spatial characteristics. Building up mathematical equations and then applying cost/constraint functions can be used to optimise (minimise) the evacuation path evacuation times. An example of this is Graph Theory (Newman, 2010) as applied to spatial or social networks. This provided useful materiel in shaping the approach herein.

In a very recent study analysed in a similar manner Newman investigated the time to muster passengers as quickly as possible during emergencies (Kezhong, Yuting, Mozi, Kehao, & Kai, Nov. 2022). It interestingly tried to bring together evacuation data published from general buildings and correlate that to passenger ships. It found that this correlation was not always best and, in some instances, could actually work in opposite to each other and make things worse. As this is a very new publication, this thesis does not cover these aspects. It will be included as a recommendation.

More complex representations can utilise advanced spatial simulation methods such as cellular automata (fixed spatial framework such as grid cells and specifies rules that dictate the state of a cell based on the states of its neighbouring cells) (Sol, et al., 2011). Another choice is the use of Agent Based Modelling (ABM), characterised by software agents that have purposeful behaviour and can act, react, interact, and modify their environment while seeking a safe objective (Baocheng, Zhen, & Xiang, 2017). Limitations to such systems are computing power and efficiencies, requiring extensive resource and schedule float – if they can be solved at all for realistic scenarios.

Many evacuation models are on the market (Lee et al., 2003), (Ronchie, 2021) that handle complex ship configurations using advanced techniques such as ABM (Lang et al., 2014). The ABM techniques employ a bottom-up approach in which each agent behaves by a defined set of rules. Their interactions are played out and emergent behaviours are found which are not intuitive (see Bonabeau, 2002 and Epstein et al., 2011). Literature discusses the benefits of using ABM include benefits such as individual discretisation, the establishment of rules for human decision making, and emergent behaviour arising from

crowding (see Bonabeau, 2002; Epstein et al., 2011 and Zhan & Chen, 2006). However, none of the references refer to the specific area of ABM for Navy ships, as research in this area is limited to passenger ships only (Baocheng, Zhen, & Xiang, 2017). This method is very resource hungry, however supplies useful insight into the issue of human behaviour.

Another technique is Case-Based Reasoning (CBR) that can be applied for solving the 3D layout design problems of ship compartments (You-Shen et al., 2001). Design tasks are used with case indexing constructions, with the design task oriented to allow indexing models based on artificial neural methods and processes for compartment layout based on CBR. The CBR design includes 3 steps:

1 Presentation of *a priori* case knowledge
2 Indexing of relational cases (similarities)
3 Validation of the identified cases and outcomes.

This method, however useful in its approach to understanding layout specifics and using a priori knowledge makes it difficult to implement it in an efficient manner.

You-Shen et al.'s (2001) research introduces the strategy of using case indexing based on Artificial Neural Networks (ANNs). This study of new compartment layout design cases presents an opportunity to use neural networks in developing ship layouts by ANNs to learn to decide similarities in compartment layouts.

The analysis of human behaviour during emergencies has been explored (Brown, 2016). The analysis focussed on passenger's alarm response time and looked at the total assembly time metric. An experiment of 5582 passengers was carried out with the result that responses were modelled as a lognormal distribution which were later analysed and normalised to supply a single distribution for each ship type. Specific outcomes showed that cabin and public area outcomes were different and that distributions should be developed for each ship type. Adapting this data to develop response time and then apply probability metrics completes the total time taken to evacuate a ship.

Taking this strategy one step further, Tkachuk, Maltseva and Song (Application of artificial neural networks for agent-based simulation of emergency evacuation from buildings for various pirpose., 2018) have conducted research in human behaviour with respect to evacuation simulation in a building based on ANNs. They used machine

learning to precisely simulate the behaviour of all people during evacuation. They simulated reactions on being presented with obstacles and other people and predicted the impact on the main evacuation routes in advance. The consequence was the ability to make changes to the building plans in the design phase. To verify their analysis, the researchers included sample testing of building occupants.

These strategies – ANNs and CBR – are interesting alternatives to meeting emergency prediction objectives. However, they suffer the same limitations in that they are resource and schedule intensive, and cannot be readily adopted to real time, or systems design analysis which requires many iterations of a configuration to arrive at a best solution for evacuation.

These tools are often derived from building, infrastructure, or bridge design (pedestrian flow) domains to serve the interests of building escape or traffic simulations which supply the bulk of the movement data available currently. However, they are difficult to reconcile with maritime and Navy environments, especially about the real time characteristics.

Furthermore, two major mitigators to combat uncertainty have been described as acceptable means to reduce risk by the Society of Fire Protection Engineers (SFPE) Task Group on Human Behaviour in Fire (2019). These mitigators are:

1 Reducing the impact by applying a safety factor/safety margin to address the potential uncertainties
2 Using more correct data, better analysis including sensitivity, or using more complete and robust scenarios and robust models.

In addition to these two mitigators, safe route determination plays an important part in the situational awareness of evacuees trying to escape in an emergency and uncertain circumstances. Current prediction approaches argue that no matter how far these mitigators are pursued, considerable risk is still clear due to human behaviour in negotiating route paths and local condition or personnel progress uncertainties. The same can be said of prediction and route determination which can be better understood as an augmented stochastic process that can be introduced to decide evacuation time.

2.5 The Case for Design in Literature

Design activities place a different context to ships undertaking operations. By its very nature, designs for commercial and Navy ships look to optimising layouts and systems and show varying paths, widths, stairs, ladders, and crawl spaces, negotiating system accommodation thereby making hull structures complex. The process by which they are designed is similarly complex (Rigterink, 2014). David Rigterink explained complexity and disjointedness lead to the creation of disparate and incomplete ship design information which appears as design information created by different systems of analysis, completed by different design groups, using different tools, at different levels of fidelity. Designs that model distributed systems often lead to decisions based on disparate and incomplete information which adds unnecessary complexity when the design is transitioned from the early design stage to the detailed design stage.

The early design stage is occupied with using concepts based on experience and knowledge of the designer at hand. Designers do not have a complete picture of the space relationships of the ship and cannot foresee what one space outside their field of view/area of interest can affect another ship space. Design control operates on being able to connect spaces visually, one that includes spaces and connections and presents the designer a picture of the skeletal makeup of the ship. Network analysis connects the spaces and systems and analyses the specific connectivity mathematically, making it a useful view of the network.

Well-known software tools adapted for ship designs that can provide this connectivity include:

1 DEMON (Boulougouris & Papanikolaou, 2002)
2 IMEX (Dongkon et al., 2004)
3 AENEAS (Meyer-Konig, Valanto, & Povel, 2005)
4 VELOS (Lang et al., 2014)
5 MaritimeEXODUS (University of Greenwich, 2022)
6 EVI - Advanced Pedestrian Dynamics tool, Brookes Bell.

The novel intelligent ship evacuation model, IMEX, was introduced by Dongkon, (Dongkon, Hongtae, Jin-Hyoung, & Beom-Jin, 2003). This tool can solve problems caused by complex configurations and motions of a ship. AENEAS and

MaritimeEXODUS are grid-based models which model the floor plan of the ship by dividing the ship into uniformly distributed rectangular grids and people are only allowed to move from one grid to another, step-by-step. MaritimeEXODUS has incorporated stochastic techniques to decide confidence levels in the final results. This approach also has limitations similar to ABM.

In fact, there are several cases of evacuation simulation development, for example, Zheng and the team (Zheng, et al., 2009) discuss seven methodological approaches for crowded evacuation. They concluded that different approaches should be considered for different scenarios and simulations, however noting that Agent Based Modelling (ABM) is ideal for these situations. ABM, as noted before, is not suitable for real time application due to being resource heavy and uses significant computer time due to combinatorial optimisation processing time.

MaritimeEXODUS has been shown to be a flexible and useable tool that maps the layout topography, making it useful for evacuation studies, and most importantly, can analyse detail at the local level. It has been used for Navy studies in the evacuation modelling of QE class aircraft carriers (Andrews et al., 2008). Andrews articulated that the designers' aim is to develop a design rationale behind the operational use of the ship based on integrating human factors, operability, space allocation for systems and personnel movement simulation. The research has led to the recommendation that designers should use innovative tools for the purposes of ship preliminary design, without the use of expensive and resource intensive CAD approaches. This approach was supported by Casarosa (2008) in his PhD thesis. The doctoral study successfully argued that it was possible, helpful and impactful for preliminary ship design to be conducted by integrating ship configuration design with simulation of crewing functions, such as operations and evacuation, a feature that can be integrated into the prediction framework developed in this research.

Integrating personnel movement simulation into preliminary ship design introduces the assessment of onboard operations at the front-end of the design process. It informs the design and enables improved operability, while the design is still amenable to changes and can be improved.

A further example to tackle the simplification of the growing complexity of tools was the investigation into the use of Agent Based Modelling (ABM) software EVI and a specific analysis technique – the Batch Non-Homogeneous Poisson Process (Batch NHPP). (Hifi 2017). The results were encouraging in that a path prediction solution was found. However, the simulation suffered the same issues mentioned above, in other words, a high degree of complexity and a high level of human and computer resources, and schedule and computer time expenditure. Ultimately, not enough time was allocated to this Master's research study and the research was terminated early.

Systems Engineering (SE) processes need quick, efficient, and quasi-accurate data to conduct needs, requirements and preliminary designs during a ship's acquisition life cycle, as specified in the Electronic Industries Association (EIA) standard EIA 632, 'Processes for Engineering a System' (SAE International, 2021). The acquisition life cycle phases are the most important phase of the eventual acquisition of the product. To meet the requirements of SE efficiently and expeditiously in this specialist domain, simple but correct means are needed to frame the ship's evacuation performance to aid ship layout studies and support the rest of the SE acquisition and support life cycles.

Rigterink (2014) discusses that design drivers appearing from compartment topology and the analysis of movement interactions between compartments do *not* require complex 3D CAD modelling or design simulations. The design drivers can be used by naval architects to gain clear oversight and insight into the implications of design layout decisions in the earliest design stages, resulting in improved evacuation designs very quickly. The solution can be modelled to the lowest detail needed to reach the final design outcome. The network approach is ideally suited to solving these issues.

However, while an RTLS system negates the requirement to model human behaviour, in the design space, a level of human behaviour and uncertainty requires inclusion. A method has been proposed that uses stochastic processing for the movement of evacuees by randomising the velocity parameter.

Following another tack, the pursuit to improve the prediction tools for emergency evacuation shows a lack of uncomplicated evacuation prediction tools that ideally suit inquiry and the assessment that underpins systems engineering feasibility studies and inquiries.

2.6 Concluding Remarks

This literature review has presented the current state of prediction algorithms of evacuation planning. The approaches investigated are complex, time consuming and resource heavy, to the point that they are not suitable for problems of greater size and complexity. These approaches cannot be used for either real time application or for the design of ship layouts efficiently. For the design case, layout require a fast and efficient prediction tool for conceptual studies to present options and preferred layouts early in the design process, to meet design requirements.

The implication of the literature search is that evacuation time is an unreliable factor in simulation/prediction studies, but if one can combine this with real time location monitoring data, a relative ranking of competing evacuation and firefighting stochastic options can be presented to the operator with annotated levels of risk. Uncertainty can be significantly reduced and pertains to design, where stochastic approaches (or others) combined with path prediction will help the designer and evacuation planners alike.

This literature review has found that no research or dedicated tool suits the approach for evacuation planning, specifically for optimisation of path selection. In response to this limitation, this research study develops a framework to overcome the deficiencies related to uncertainties and narrows the knowledge gap detailed in the first two chapters.

The most significant benefit is to develop the ships architecture and predict the safest and shortest route for humans to a safe evacuation point based on real time evacuee movement data; this is always the starting point for a good prediction algorithm. Design comes next and is undertaken by considering interactions and how it applies to the exit strategy. This is supported by mathematical theory and can be related to graph theory to further the understanding of ships' topology and behaviour patterns. Graph theory introduces linear programming to conduct optimisation. Nevertheless, the use of specific efficient and simple mathematical optimisation techniques of this approach for ship evacuation is limited. This is clear in Ching-Wu's (2013) research which presented a graphic-based search model.

The next chapter presents various application methods that have been considered to fit into a prediction framework for the purposes to simply and efficiently control the uncertainty in order to mitigate the final risks in solving the research problem.

Chapter 3 Solution Alternatives - Selection Prediction Approach

3.1 Introduction

Chapter 2 presented the state of the art in evacuation analysis, through a thorough critical literature review. This review showed that a plethora of tools are available to undertake evacuation analysis. Most tools are bespoken to the specific domains or interests and are not necessarily designed for maritime use.

The approach adopted in this research study is a compromise between evacuation time, utility of architecture, the level of certainty, awareness during evacuation, and the capability to apply knowledge to achieve an acceptable outcome. This research needs to make a selection of the analytical methods available that suit the overall solution, based on accuracy, efficiency, simplicity, and minimal resources. Network assessment of the ship's architecture is a most promising analytical method to solve the path prediction problem. Most importantly, the method has been assessed and has been confirmed for use for each intended purpose.

Graph Theory, which is the mathematical description of network analysis, is originally related to evacuation prediction providing useful methods to solve the research problem and is included in this chapter as the alternative to the bespoke approaches to the prediction approach. This chapter also outlines these analytical sub-methods that have been used in Industry are capable to devolve a specific issues to support the solution of the current prediction problem.

As analytical practitioners, one must balance the approach between best decision making, resources and time needed to achieve a safe outcome. Even though current research in this area is often not applicable and is minimal in the maritime context, the approach to this research is to apply proven and correct analytical algorithms which have been used with effect and accuracy to solve similar problems.

The following sections explore the Graph Theory approach adopted after careful and experiential analysis to develop a complete architectural prediction tool for the design and in-service cases. This tool will also meet the requirements of:

1 A green field (new) application in the design of new ships

2 A brown field (defined) application to be used in existing ships for sustainment, capability update and upgrade purposes

3 Real time location monitoring systems in emergency situations.

This Chapter also assesses modelling approaches that can support the Graph Theory method. These methods can be used to provide a verification by similarity to that proposed by Graph Theory. To that end, this chapter also supplies insight to some important features that inspire the adoption of a quality standard, introducing new ways to arm the evacuee and the overall process. In summary, it's not just the one method that supplies the total answer, but an accumulation of other methods that can supply a more complete picture of prediction.

3.2 Multi-Commodity Flow Modelling, an application of Graph Theory

Multi-commodity flow modelling (Dai, ZhangJ., & Sun, 2017), (MIT, 2013) is a special logistics application of Graph Theory that originated in the work conducted to optimise transfer of commodities in supply chain networks. This technique has been studied in developing train routing and scheduling with resource-constrained models based on the multi-commodity flow, by developing nodal networks and applying flow algorithms. Dai (On solving Multi-Commodity Flow Problems, 2017) found the use of multi-commodity flow techniques to the application of tracking of people was feasible with experimental results showing that the approach performed better than other state-of-the-art tracking algorithms.

The network refers to a visual structure being a group of ideas/objects/people/systems and relationships between them. Also known as a graph in mathematics, a network structure consists of vertices and edges. Here, vertices, also known as nodes, represent notional objects, such as spaces or functions that require analysis while edges are the relationships between those objects and the direction of their activity.

For example, if we are studying a social relationship between Facebook users, nodes are target users and edges are relationships such as friendships between users or group memberships.

The use of networks can be used in multiple fields for example, in the medical field where variables such as stress, peer pressure, functional fitness, nutritional quality of food and drink can be thought to be vertices in the network, and the positive and negative

relationships between those vertices are edges. In the Navy safe evacuation context, vertices represent spaces such as compartments corridors, stairs while edges are the non-dimensional entities that identify connectivity and direction.

The original concept of networks is based on the work of Leonard Euler, who in 1788 constructed the first graph to solve the now famous mathematical puzzle for the Königsberg bridges known as the Travelling Salesman Problem (TSP) with set start and finish cities. The algorithmic model that solved the TSP is based on network theory characterised by vertices and edges showing a network like structure typically referred to as the Graph Algorithm. The TSP is what is known as a combinatorial optimisation problem (Schrijver, 2005), being a subfield of mathematical optimisation that consists of finding an optimal object from a finite set of objects, where the set of feasible solutions is discrete or can be reduced to a discrete set. In mathematical terms, the problem comes down to give an n × n 'cost' matrix C = (Ci, j), find a permutation π of 1, . . ., n for which:

$\sum_{i=1}^{n} C_{i,\pi(i)}$ is as small as possible. Eqn. (3-1)

Typical combinatorial optimisation problems are the travelling salesman problem (TSP) (Schrijver, 2005) and (Yu, 2014). Graph theory is the studies of graphs (MIT, 2013), the mathematical structures used to model pairwise relations between objects..

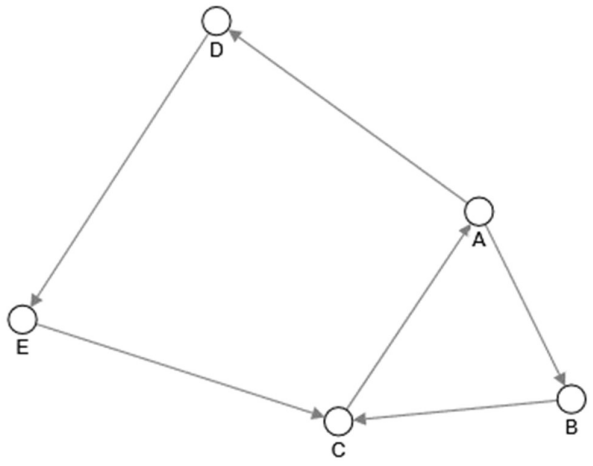


Figure 3.1 Directed graph Showing Vertices and Edges

Once a graph is defined for the problem at hand, then a mathematical algorithm is applied to decide a mathematical scheme in a series of linear equations and then optimised

according to the constraints applied. From this, network theory is applied to decide the properties of the graph network. The advantage is that network metrics can be extracted that show the mathematical properties of the network, which relate to the physical arrangement and the nature of the edges in the model. The metrics find useful quantities such as most important node, the most central node, the geodesic path length (how many hops to another specific node), the network density, which captures the number of nodes connected.

An operational planner can plan based on an evacuation network, the transferring evacuees from the dangerous (sources) to safer (sinks) locations as quickly as possible and in abstract terms and based on Dempe et al. (2019), much like the transfer of commodities in a supply chain network.

Automated approaches for creating ship general arrangements in early-stage designs have been developed, (Gillespie, (A Network Science Approach to Understanding and Generating Ship Arrangements in Early Design Stages, 2012). These approaches avoided 'black box' solutions by keeping the designer involved in the layout generation and selection process. Solutions which tended to move towards full distributed system layouts in early-stage design have only led to more highly refined CAD-style approaches requiring extensive modelling and computation time. Gillespie's research moved towards higher-fidelity three-dimensional layout models using vector-like displays which rendered a perspective focusing on understanding the fundamental underlying relationships among elements within those models. This is the case applying these network ideas to evacuation prediction.

The work led to the use network theory and science to model warship recoverability modelling (Rigterink, Piks, & Singer, Methods for Analyzing Early Stage Naval Distributed Systems Designs Employing Simplex, Multislice and Multiples Networks, 2014). Network theory has now evolved into a tool to investigate not only topographical features, but relationships in systems such as electrical or firefighting systems, which has led to being useful to simplifying model ship systems in early-stage ship designs. This conclusion has validated this premise by establishing that a relationship between graph theory/network science and evacuation is a valid one (Capizzi & Marian, 2019; 2020; 2021)The mathematical representation for evacuation paths can be modelled using optimised linear programming techniques (graph theory algorithms) which are

constrained by cost and path capacity or any constraints which identify difficulties to determining the best path in the minimum amount of time. The shortest path is defined by an ideal passage time for safe evacuation. Optimisation minimises quasi cost and loss function, which is based on local path conditions and personnel route capacity. The data used to decide passage velocity is based on the building industry and covers a myriad of circumstances, too many and uncertain to be identified as deterministic. The consideration of using random probability to decide a likely evacuation performance is based on stochastic processes.

3.2.1 The Application of Network Modelling to Evacuation Analysis

Network modelling can be applied as a proper path optimisation model to calculate evacuation time. It is well suited for adaption to physical systems and evacuation analysis as it can be adapted to run as an interactive optimisation algorithm implemented using Microsoft Excel.

This approach is flexible and adept to conduct initial systems engineering trade-off studies, requirements analysis and conceptual design of ship evacuation routes, see (Gillespie, 2012) and (Rigterink, Piks, & Singer, Methods for Analyzing Early Stage Naval Distributed Systems Designs Employing Simplex, Multislice and Multiples Networks, 2014). Various evacuation constraints concerning fire, toxic gas and structural damage can be modelled out quickly and efficiently by changing path capacity and cost functions and managing velocity outcomes. A solution cannot be found if persons have no capacity to find potential death traps in a design or find alternative paths to reach the destination.

With the capability to re-configure paths (edges) in real time, evacuation capability can change dynamically as a moving vista of path changes is recorded due to fire fronts or environmental transients in-situ, as they occur. In a real onboard scenario, personnel location data can be updated in real time to aid evacuation, provided information can be relayed to supervising personnel.

The graphing algorithm when applied to ship designs is characterised by similar traits:

1 The ship layout can be represented as a modified TSP with paths, constraints, and capacities along modelled edges. The level of detail is left to the designer.
2 The ship is represented by a routing directed network using:

a. vertices – describing transition points forming compartments and rooms
b. edges – forming corridors, passageways, and stairs
c. sources – compartments or spaces
d. sinks – the final destination

3 Adopting a linear programming model allows for degradation and constraints with time. A notable difference for ship design compared to the TSP is that the start and the end of the travel are different and defined for each space.

This research study covers the above points and presents a fresh schema for ship evacuation using the quasi -multi-commodity flow technique. Once the path is found, a first order hydraulic model is introduced to decide evacuee flow properties such as path progress and delays. The approach is a quantifiable evacuation means that can support an engineering decision-based management approach, based on analysis and judgement. Hydraulic models are simple flow visualisations constrained by a boundary and described by a set of equations (Dai, ZhangJ., & Sun, 2017). Evacuees flow from node to node (e.g., from a corridor to a stairwell), with the speed of their movement dictated by the equations that form the model. The evacuation time (i.e., the time predicted by the hydraulic model) utilises a series of expressions that simulate test data tests and observations to a hydraulic model of human flow. Modelling criteria relate to effective width, population density, speed, flow characteristics, time for passage through a compartment, and transitions between compartments. Each of these considerations is discussed in detail by Gwynne and Rosenbaum (2016).

3.3 Data Sources for Evacuation Prediction

Most often, the analysis of available data sets the direction for developing a solution. Data is the basis of problem solving and the gathering data shapes the comparison of effective strategies from ineffective ones. For example, the model type is dependent on the macroscopic or microscopic viewpoints. The two different views can occur at the same time, and can be compared for their performances, or phased in to supply both levels of detail and generality needed. The available data can decide which approach appeals more to achieving the aims of the user.

Typical data of interest that affects egress time and is specified to predict evacuation performance is based on the following criteria:

1 Evacuee velocity based on fitness, age, and capability
2 Evacuee velocity based on flow density
3 Topography/path movement data relating to widths (boundary layers) and path transitions
4 Designs relating to evacuee movement velocity when confronted with constraints, such as lighting, smoke, gas, and obstacles
5 Maximum movement speeds against density of evacuees in a width constrained path
6 Movement velocity proceeding up the stairs and downwards
7 Derived specific flow data based on velocity, effective width, and people density.

This data relates to two main aspects: the individuals' capability and the people's movement in constrained flow conditions. The modeller uses this data to predict the safest and shortest route for humans to the safe evacuation point. The solution lies in the definition and detailed analysis of spatial properties such as specific topological path geometry, geometric or geographic entities of routes (Society of Fire Protection Engineers, 2016). Modelling techniques may use mathematical representations of spatial properties using the vertices and edges method to better define the spatial characteristics and then apply optimisation/cost function properties to characterise the path length (Society of Fire Protection Engineers, 2019).

3.4 Further Modelling Representations

More complex representations can utilise advanced spatial simulation methods such as cellular automata (fixed spatial framework such as grid cells) and specifies rules that dictate the state of a cell based on the states of its neighbouring cells or agent-based modelling. Software agents that have purposeful behaviour can react, interact, and change their environment while seeking safe aim (Macal & North, 2007). However, these techniques are difficult to implement in a simple and effective manner. They are not considered conducive for ship design purposes due to their modelling and computational overheads and ability needed.

Sources of data are related to ship drawings and technical data for any vessel topology. This data is similar for Navy and non-Navy designs. As such, an analysis approach suits a simple graphical representation to undertake inspection at a macro or micro level.

Most movement sources, as mentioned above, are industry-based, but refer to specifics that vary minimally when associated with ship designs, such as movement velocity but can be adapted to ship conditions appropriately (Society of Fire Protection Engineers, 2019) to take into consideration ship movement and environments. These are discussed in next section.

3.5 Ship Configuration Designs

The two main areas where design activities can influence escape and evacuation are onboard training as part of the Integrated Logistics Support (ILS) package and the design of general storage/accommodation arrangements. These two conditions form the mitigation basis for evacuation processes (Carnie & Hicks, 2000). This basis defines a quality standard for escape and evacuation software use in military ship assessments. They advocated that a proper understanding is required of ship motion, ship heel, lighting and stair/corridor/hatch dimensions, deck configurations, outside decking and how they affect the evacuation time/process, and how these issues interact. Technical data sources on the levels of lighting and its effect on escape onboard ships rely on the ability of personnel to recognise signage in a smoke-filled environment (Carnie & Hicks, 2000). Lighting affects visual acuity and human behaviour response. Important main sources of data come from Industry such as the SPFE Handbooks (SPFE Handbook of Fire Protection Engineering 5th Edition, 2016), and Maritime sources such as the IMO, (IMO, 2016).

Simulation modelling has been difficult when faced with so many variables and influencing parameters. Examples of design considerations are ship operations such as the function of crewing, maintenance, engineering support, spares, and onboard training. An example of the system dependencies is the layout of machinery spaces which is dependent on available resources, available technical documentation, spare parts, and consumables to conduct maintenance activities. Here systems are related to external influences not directly interfaced to system layouts.

Another example which is not a normally associated topic is the issue of training drills. Since the sinking of the Titanic, the standard practice of conducting training drills happens regularly during a voyage. Regularity is also conducted to reinforce training practice as per SOLAS Regulation III/19. the allowance for training and training aids is also an important influence on the configuration of a ship.

Optimising the layout for operations, logistics, training support and associated evacuation requirements is a complex design issue where visualisation is critical to understand these and other related requirements. Therefore, pathways and connecting spaces/routes should be designed beforehand with training in mind, and the systems integrated after. Design trade-off studies and concepts are an important activity for the design ship layouts.

3.6 Consideration of Human Behaviour in Evacuation

Detailed consideration of human behaviour is not a primary focus of this research. Extensive human behaviour modelling for real time systems is not needed. It is notable that, including behaviour in the formulation of an evacuation algorithm, drastically increases the complexity. Consequently, this research assessed the view that stochastic parameters can be used for pseudo behaviour modelling, which is realistic at least at the functional level.

However, as discussed, architecture modelling brings out emergent movement behaviour, and this is an important aspect of Graph Theory.

The ideal requirements for evacuation analysis have been listed by Kim et al. (2004) as:

1 development of the geometric model for the evacuation analysis (a method is presented herein)
2 the evacuation analysis algorithm – the primary focus of this research
3 the behaviour of people under normal and hostile conditions – behaviour is not a requirement when the system is incorporated in real time
4 the effects of ship pitching, rolling, and listing – these effects can be added as required using existing data as a function of crew movement velocity and also mitigated when the system is incorporated in real time.

A geometric model must be rendered in detail and forms compartments, corridors, stairs, and communal meeting and eating areas. The evacuation algorithm is derived from traffic control or particle movement studies, prevalent in airplanes and buildings where multitudes of people are concentrated. A full analysis of human behaviour in emergency situations deals with human factors that are hard to analyse by experiments. These factors include cultural differences, gender, age, behaviour under panic, and so on (IMO, 2016). It is not possible and would be highly unethical to try to run experiments that simulate realistic behaviour in a crisis situation (e.g., replicating real panic in a crowd).

For example, data from the Fire Protection Engineering Handbook (2002) suggests that panic behaviour rarely occurs, but that re-entry behaviour is quite prevalent. For example, the 1956 Arundel Park Fire in the US showed one third of the evacuees had re-entered the building as most evacuees fought the fire (Blanchard, 1956). This behaviour is a probable outcome onboard a military ship. The effects of pitching and rolling, which are not significant in ground buildings, are considered as the dominant factors in ships. They have direct effects on the behaviour of people and are especially critical for senior people and those with physical disabilities (Lee, Kim, & Park, 2003).

All these behavioural aspects make simulation modelling difficult, but the effects of human behaviour are considered and modelled as an added level of uncertainty, which increases the realism of the simulation.

3.7 Microscopic View of Evacuation Simulation

A truly representative microscopic view to prediction considers all the interactions prevalent in an emergency. As mentioned previously, Zheng et al. (2009) discussed seven methodological approaches for crowded evacuation based on their analysis ABM was considered ideal for these situations.

Tavares (Evacuation Processes Versus Evacuation Models: "Quo Vadimus"?, 2008) showed that over 40 different evacuation models had been used for different types of enclosed environments, such as buildings, aircraft, ships and trains. The emphasis in these models was steering towards dependence on the simulation capabilities, and not on the evacuation process itself. Tavares concluded that for complex ship situations, a systems view is needed with the evacuees included in the model, such as, models that can simulating the evacuees' interactions with the structure, the presence of other evacuees and the emergency is needed. These thoughts, developed 14 years ago, align with the aims in this research, noting that interactions are mostly manifested as movement data used which can support the basis for this research.

As noted, ABM is ideally suited for this approach for conducting detailed and emergent human behaviour. This technique is supported by Bonbeau et al. (2002) who consider it unsurpassable for complex and inhomogeneous agents. The reason for this assertion is that using Agents in this manner can negotiate the path topology based on their interactions and can make decisions in accordance their knowledge rules. However, ABM

needs high level computer resources due to combinatorial explosions and cannot be solved for realistic size systems with present computers. In addition, ABM needs systems engineering specialties in the areas of hull integrity, evacuation analysis dependencies, and relationships between the various parties involved in the disaster. Nevertheless, ABM is highly suited for detailed view, such as the discrete layout of compartments, or corridor transitions.

Figure 3.2 presents a complex evacuation and its simulation which is based on the interactions between occupants, crew, damage control party, the Damage Control Centre (DCC), the structure and the fire. Figure 3.2 also shows evacuee interactions – labelled A to F – which can be simulated using ABM techniques. However, this simulation is interlaced with complex machine operations which presents a combinatorial processing limitation. For example, a ship's emergency simulations need to consider the following interactions, between i) crew–structure; ii) crew–crew; iii) crew–fire (in case of fire events); iv) fire–structure; v) crew – damage control party; vi) damage control party – fire; and vii) the surrounding in which the disaster takes place. The endpoint is to decide and control the disaster margin. And the process showed in Figure 3.2 is about relationships!

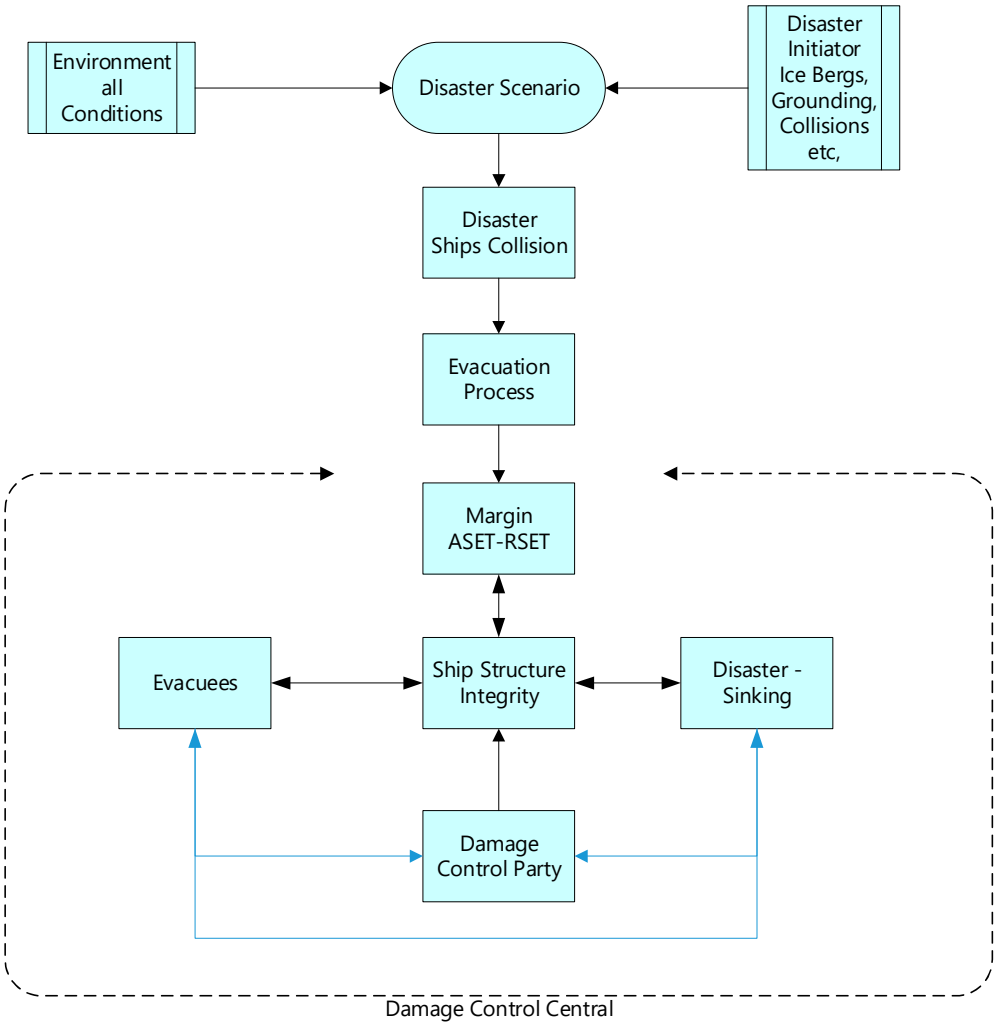


Figure 3.2 Complex Disaster Simulation Requirements

Agents can be modelled to show different behaviours, such as a crew's manifest can stand for a typical manning profile for a military ship. Agents with different behavioural characteristics and decision capabilities (e.g., fully trained crew compared to new recruits) can be tracked to check performance so that Item 4 above can be further explored.

More recently, Epstein et al. (2011) has brought together a 'novel hybrid of two fields', to model an aerosol release in Los Angeles and concludes that 'this new approach can be powerfully applied to arbitrary population centres, offering an unprecedented preparedness and catastrophic event response tool. Epstein (2011) demonstrated that the microscopic modelling of individuals brings an unprecedented advantage over other

methodologies by the transparent emergence of behaviour which is not included in the programming or simulation. Epstein argues that people do not optimise as they have limited information and skill sets. People act out/decide by using simple rules and norms, which are biased; their decision making is based on partial reports and expressed as behaviours to their peers and their belief of situation awareness. Epstein finds this as 'bounded reality' and presents the modeller a very difficult task in performing evacuation planning. This is another aspect that limits understanding and situation awareness.

3.8 System Dynamics – A Macroscopic Supporting Graph Theory

A causal loop diagram representation based on current systems understanding defines detailed interactions as shown in Figure 3.2. Simulation complexity is needed to effect better dynamic descriptions to understand the system function. Note that influences extend to both sides of the Available Safe Egress Time (ASET) minus Required Safe Egress Time (RSET) (ASET minus RSET) calculation. To reflect the range and complexity of these interactions, any quasi-real time simulation will require complex relationship modelling.

Beyond the approaches described thus far, a macroscopic systems view can be implemented using systems thinking. The evacuation system includes the ship, the passengers, the evacuees, the controlling mechanisms, the communications system, the safety appliances, the environment, and so on. These individual subsystems can be analysed as a total system of subsystems using a Systems Dynamics approach. This approach couple's behaviour and its causes and effects on the evacuation process (Kirkwood, 2013). Kirkwood uses these diagrams to describe circular feedback chains of cause and effect. More formally, a feedback loop is described as a closed sequence of causes and effects, as a closed path of action and information. An example of this is a stock and flow model and is represented in Figure 3.3.

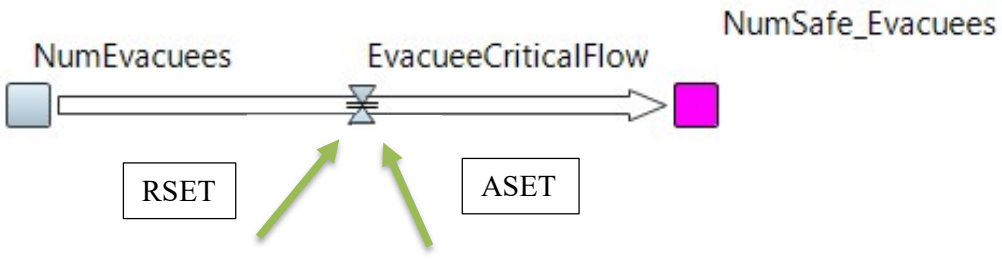


Figure 3.3 Stock and Flow Diagram

This diagram shows two buckets being the stock (evacuees onboard), the number of total evacuees in the first bucket prior to evacuation and the total number of safe evacuees in the second bucket after evacuation. The valve is the people flow in people per seconds. The valve is affected by RSET and ASET. The number of evacuees and safe evacuees is determined to be a constant for a positive safety outcome. The flow is governed by the valve, which opens, and closes based on flow density, path transversals, path width, traffic, resistance (delays) and the parameters which define RSET. The valve can, however, be turned off if the gap constraint RSET exceeds ASET. As a system, the behaviour can be represented as a goal seeking solution, the number of evacuees starts below a goal level and over time moves toward the goal, unless the gap constraint is exceeded and causes the valve to be turned off. This system behaviour is shown in Figure 3.4. This behaviour is as expected, where the number of evacuees follow an asymptotic goal when the total number of evacuees are safe. The two lines signify performance as negative or positive performance quantities, i.e., the quantity of interest starts either above or below a goal level and over time moves toward the goal. In this example, evacuees are considered about the goal level.

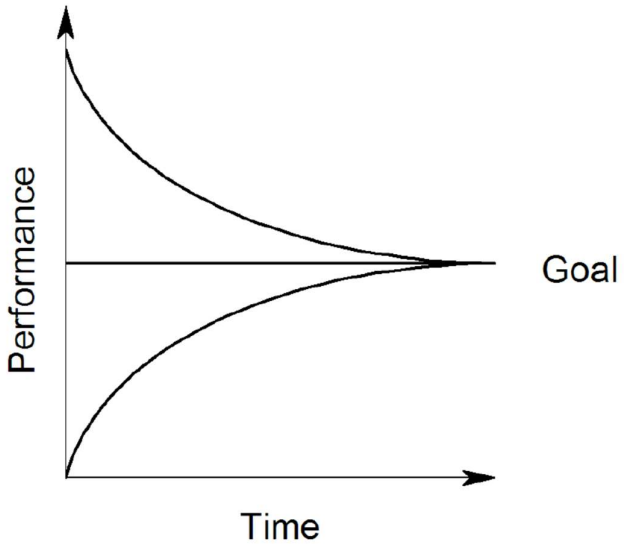


Figure 3.4 Goal Seeking Behaviour

3.9 Quality Standard Knowledge Requirements

The quality standard for escape and evacuation software suggested by Carnie and Hicks (2000) found that such a standard is needed for any evacuation planning approach. The following principal thought processes need to be considered when deciding how a quality standard would add benefits in deciding evacuation planning outcomes.

1 Understanding how human factors affect the evacuation time/process and how they interact, namely:
   a. Personnel age, fitness, and composition
   b. The influence of training in a successful evacuation may well be the strongest, especially if it is regularly reinforced by drills
   c. The influence of organisational setup and rank impacts evacuation
   d. Defining how evacuation time (RSET) reduces the safety risk to be So Far as Reasonably Practical (SFARP). SFARP is the standard context by which safety is compliant to safety regulations.
2 Instilling a sense of duty to evacuees in response to disaster instances by supplying specific roles to evacuees in the emergency process
3 Having a better definition of the risk of overall fatalities. Is it practical to run under a performance measure that uses only a defined time for escape based on best estimates
4 Deciding whether personnel training is indeed the strongest influence when reinforced by drills, irrespective of the ship's configuration.

These items in consideration, support situation awareness and capability knowledge and experience.

For the first item – human factors – several papers tackle most of the issues found. One example where this applies is the papers by Colwell (2005) and Deere et al. (2008) who supply Navy personnel data in support of all the issues found and can be applied to the maritime context.

3.10 Concluding Remarks

This chapter presented ideas and methods that could be considered to develop an evacuation planning roadmap for ships. There are a number of promising methods that can be used to assess the evacuation process. A simple tool is needed for both specialists

and non-specialists alike. The simple tool is fundamental to all the ideas and methods presented.

The research has shown that development of this application is viewed quite challenging and is a radical departure from the standard methods/approaches currently available to supply simple and fast tools. Architecture and evacuation are linked and is an integral part of the ship's armoury for operations and survivability when needed.

For the purposes of this research, the focus is on developing the framework including the general method and tools and algorithms to solve the research problem. The development of related methods and algorithms that employ an alternative micro or macroscopic views of the enfolding situation will depend on the context of its use.

Evacuation is understatedly a highly complex issue, as highlighted in this chapter, and no individual design predictions can be adapted to find the actual evacuation prediction. Nevertheless, earlier research has uncovered many laborious and complex undertakings utilising significant intellectual resources as well as cost and schedule into the formal predictions of emergency evacuation within a simplified context of human behaviour. It can be common thread for Navy design to be used for both macro and microscopic viewpoints.

The conclusion for this Chapter is the adoption of using Graph Theory as a method that can best meet the expected outcomes, and depending on the modelling context, these other methods can also be employed to add or detract views.

Chapter 4 Further Analyses of Other Relevant Ship Accidents

4.1 Introduction

The evacuation literature presented in the first three chapters details the various analysis approaches and elements associated with evacuation prediction. An emergent clear issue is that there are myriad techniques that provide a view of evacuation prediction. However, the approaches appear to be context driven. To clarify the objectives of this research, this chapter presents another two maritime ship evacuations to focus on the need to further assess the critical issues presented in Chapter 1 and lay the foundation of developing an emergency crisis argument to be introduced later in Chapter 5.

These maritime accidents are significantly different to the standard scenario-based evacuation analysis in use today (IMO, 2016). A notable issue of earlier accidents is the absence of correlation between the time for a ship to sink and the number of casualties. The examples presented here seek to understand the requirements of evacuation prediction, its causal context and scope. Stated again, the significance of using evacuation time is not the sole arbiter of a safe evacuation outcome, but relates to the time to egress, plus the influence of situation awareness and the application of capable knowledge, experience, and training to affect a safe outcome (see Emergency Crisis Triangle, see section §5.3). The causal influence guides in the type of prediction to be covered.

All three experiences led to very different conclusions. It highlights the need to improve the evacuee's control of the situation and to make strategic decisions based on what information is available at any given time. A possible technique mitigates the risk to evacuation by tackling the deficiencies identified in the two fascinating scenarios presented below where one would argue there shouldn't have been any fatalities. The chosen ship sinkings were selected because the outcomes were unpredictable and were post Titanic ships with the full IMO safety framework in place. The two ship cases are:

1 The Britannic, a sister ship to the Titanic and was chosen with because specific watertight improvements were made and had incurred similar contextual damage below the waterline near the bow.

2 The SS Principessa Mafalda, chosen because the sinking occurred in light conditions resulting in minor damage within proximity to shore and rescue services. This ship was also post Titanic and SOLAS designed had been designed into the ship.

4.2 SS Titanic's Sister Ship: The Sinking of the HMHS Britannic

The *SS Titanic*'s sister ship, the *Britannic* was a converted hospital ship (due to World War 1) which left from Southampton for Moudros in Greece on 12 November 1916. The *Britannic* was carrying 1065 people (673 crew, 315 members of the Royal Army Medical Corps and 77 nurses). It would be her sixth voyage in the Mediterranean Sea. The *Britannic* had undergone safety modifications to the compartment watertight design in the wake of the *Titanic*'s sinking 4 years earlier. More lifeboats were added, and its watertight compartments (which featured doors that allowed the sections to be isolated from each other) were increased to 17 in number, 5 of which were raised from E deck to B deck. These modifications were a significant change to enhance survivability and stability requirements by increasing the watertight compartment bulkhead capability and more than doubling the number of lifeboats (Michailakis, 2021).

At 8:12 am, the Britannic hit an underwater mine or was hit by a torpedo in the lower forward part of the ship's bow. After only 55 minutes, the *Britannic* rolled over to her starboard side, the funnels began collapsing and the deck machinery fell into the water as the ship vanished into the depths. It was 9:07 am. In total, 30 lifeboats had been lowered into the water. While most people were saved, 30 people died.

Compared to the *Titanic*, the rescue of *Britannic* was abetted by five factors:

3 Less people on the *Britannic* with 1065 people compared to the *Titanic*'s 2208

4 The *Britannic* sank during day light, the *Titanic* was at night

5 The temperature was higher 20 °C compared to −2 °C for the *Titanic*

6 Significantly more lifeboats were available, 30 were lowered and stayed afloat compared to *Titanic*'s 20 on water

7 Help was closer, arrived less than two hours after the first distress call compared to three and a half hours for the *Titanic*.

Casualties were due to the initial blast and later drownings.

Evacuees were more in tune with the situational awareness of the events because daylight provided a sense of security, with people finding rescue boats in the proximity added to their sense of self security.

This sinking shows how reliance on evacuation time as the focus of prediction analysis leads to mistaken outcomes. Several factors made a difference to the lower death count for this sinking as compared to the *Titanic*, namely, design enhancements (lifeboats and bulkhead redesigns), daylight evacuation and favourable environmental conditions. These differences lead to the conclusion that the individual passengers had applied and capable knowledge, understood the dynamic situation and were aware of timing. These factors saved the situation for the *Britannic* survivors. However, countless ship sinkings still happen every year and many deaths still happen as a result.

Of specific interest is that even though bulkhead watertightness capability was increased on the *Britannic*, it sank in 55 minutes, as compared to the *Titanic* in 2 hours and 40 minutes. This is despite the lessons learnt from the sinking of the *Titanic*.

The implications arising from this accident point to the importance of situational awareness, as the design changes made post Titanic were less of an impact to timing and passenger movement.

4.3 Post-Titanic Sinking: The SS Principessa Mafalda

The *SS Principessa Mafalda* was an Italian passenger cruise ship that was considered to be in poor condition (Heckman, 2011). On 25 October 1927, while sailing off the coast of Brazil, a propeller shaft fractured which damaged the hull, with the result that water was being taken onboard. Complicating the issue was the fact that watertight doors could not be fully closed. The ship sank slowly in the presence of rescue vessels being 15 metres in proximity, but confusion and panic resulted in 314 fatalities out of the 1252 passengers and crew on board the ship. Conditions were calm and yet, there were many casualties. The sinking resulted in the greatest loss of life in Italian shipping and the largest ever in the Southern Hemisphere in peacetime.

In the aftermath, authorities assessed what had happened during the emergency. Rescue ships such as the *Anhela* was only 15 metres from the bridge of the *Principessa Mafalda*, yet people tossed themselves into the shark infested waters. There were reports of passengers shooting themselves, yet this was not the *Titanic* in icy waters with rescue ships far distant. The passengers and crew behaved as if it was re-enacting the *Titanic* disaster. The ship's doctor ran back to get his 1500 Lira explaining that he was 'used to the waves'. The ship took approximately 6 hours to sink!

The prime causes for the fatalities have been attributed to unrealistic awareness of the situation, such as the notion that "bad" luck attributed to the ship *Titanic*, the coupling with fear, uncertainty with the future and the 'macho' behaviour – all contributed to the catastrophe. This example points out that organisational leadership, being offered direction and being situationally aware are discriminating factors in this disaster.

In the context of evacuation methods stated beforehand, no approach would be able to predict the outcome of this disaster. It reinforces the argument that evacuation prediction cannot be precise in its solution because uncertainty and expectation make any solution unreliable for this case. However, if onboard operations adhered to the principles articulated by the Crisis Emergency Triangle, the outcomes may have been very different.

4.4 Concluding Remarks

These examples further highlight the need to understand the architecture and to relate this to the provision of communications, direction, and supplying guidance in an emergency. Furthermore, evacuation time is certainly not a discriminator for the development of a prediction algorithm. Supporting this is a graph, presented in Figure 4.1, that shows ship sinking time and how it relates to evacuation success. The analysis is from data spanning over 40 years of ship sinkings (Brumley, 2002), shows that no definitive trend is observable. Bromley's research included two types of vessels, vehicle roll on/roll off (RO-RO) ships and Passenger Vessels. Irrespective of type of ship or evacuation situation, each data instance is different.

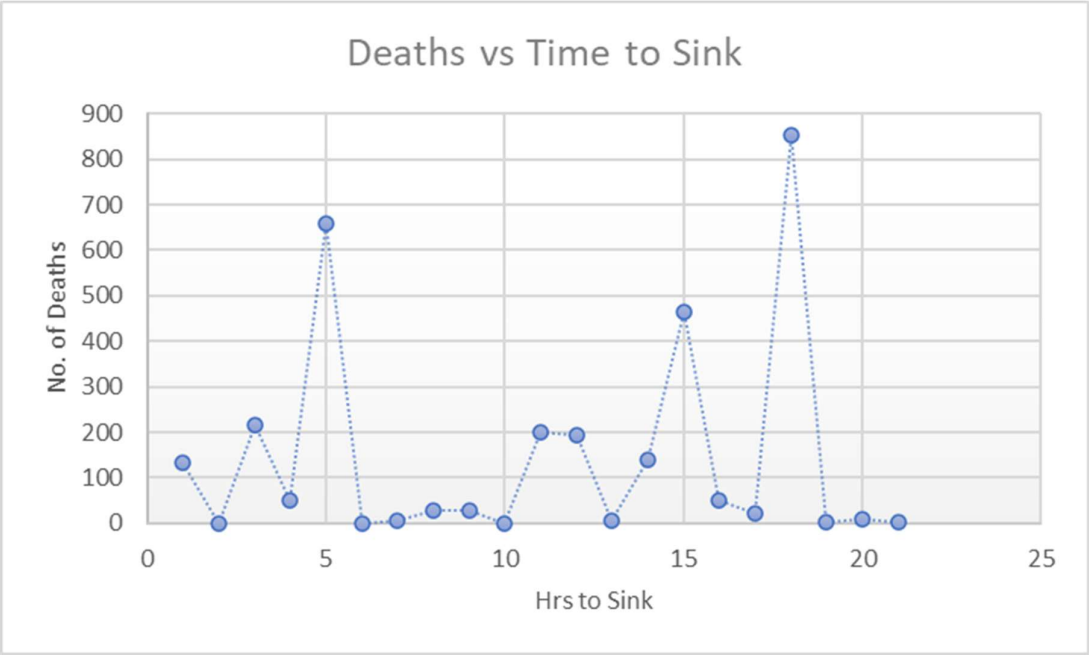


Figure 4.1 Death vs Hours for Ship to Sink

Emergency evacuations at sea are faced with changing situations, a combination of a multitude of variables, and hence vastly different. The success of the evacuations cannot be forecast. This conclusion leads to questions: what is the benefit of current evacuation tools? What purpose do they serve in the pursuit of evacuation predictions? While evacuation tools can certainly be of use in a design environment, will they be of use in real life evacuations?

These are the confronting issues concerning evacuation prediction, and as argued in Chapter 9, that the implementation of a RTLS system will be most beneficial outcome because it allows for persons to follow an evacuation procedure which is being updated according to the emerging emergency situation.

These two scenarios highlight very different circumstances in terms of evacuation elements and their impact on lives lost. It is argued that it is not possible to account for all the complex factors affecting evacuation prediction, especially those that are not in the evacuees' control. The fatality metrics highlight the need to consider these aspects in this research.

The nature of external factors concerning a person's ability to negotiate a safe outcome, appears to be more about the external factors that cannot be controlled that eventually govern the evacuation.

Therefore, it is important to understand the full extent of ship sinking data to characterise the aspects and trends. The use of stochastic processes to capture randomness in probability analysis will help evacuation planning to be more attuned to the risks involved. Also, covering the majority of causal factors in an analysis will enhance safety.

To overcome this, the next chapter refers to evacuation frameworks, which outline approaches and techniques to be used to evaluate evacuation in a standard and consistent approach for which ships can be certified as meeting policy and procedural requirements for evacuation.

Chapter 5 Pieces of a Framework to Solve the Problem

5.1 Introduction

The myriad of uncontrolled variables makes the evacuation modelling extremely complex. Complexity makes it difficult to use approaches. To that end, ship evacuations in the earlier chapters have been included to show how vastly complex and different ship sinkings are from one another. This Chapter presents the methods behind the application to apply Graph Theory to solve the research problem.

A framework is a structure intended to serve as a support mechanism to develop the prediction method and extend it to make useful for evacuation planning requirements.

The framework builds on the review of the relevant literature, assesses the limitations of the current methods, explores the salient points, defines the solution techniques, and develops the prediction method to solve the research problem.

Specifically, the framework requires applying simplification to the clear complexity of evacuation prediction and its influences. Graph theory allows for this simplification to occur, and so does the introduction of assessment frameworks which overcome the need to simulate every characteristic of an evacuation.

Network flow plays an important part of mathematical research in various fields such as traffic simulation, system dynamics and control theory, and variational inequalities where it was assessed that network flow methodologies are the most efficient (Dempe, Dhamala, Nath, & Pyakurel, 2019). Flow is a necessary component of evacuation.

A framework for emergency prediction for sea is a set of rules, methods and resources that ideally meet the policy and planning requirements and suit inquiry of evacuation ‘as quickly as possible’. To aid this framework environment, technical data is often derived from the building, infrastructure, or bridge design (pedestrian flow) domains and create ample bulk movement data from which to create stochastic data sets. Data can simply be related to characteristic evacuee movement data sets, which are based on age, fitness, and station to decide on likely movement velocities.

An efficient protocol to aid simplification in design assessments is System Engineering (SE). This approach which uses user and customer requirements allied with functional data to enable consistency, accuracy and efficiency to conduct conceptual designs during a ship's acquisition life cycle. The capability to carry out complex and many iterations is not to be underestimated and is core to solving the architecture and prediction problem. This ability to generate many analytics to form a more complete conceptual design will allow capturing more options and knowledge in the assessment process. Additionally, prediction capability needs to be in the hands of non-specialist resources to further inquiry and knowledge in this area of research.

5.2 A View to Complexity

A picture of complexity for this research is shown in Figure 5.1. System Dynamics can supply a detailed and complex model of the evacuation system and develop the macro system behaviour . This macroscopic view, assessed as part of this research, conveys the relationship complexity and the activities involved, shapes the curve presented in Figure 3.4 as a function of time. The curved arrows in Figure 5.1 specify the relationship direction and the plus or minus sign shows whether it promotes or lessens the impact on the target. Topics involve uncertainty and detrimental environments changing dynamically, where both parameters and represent feedback loops as discussed in Section § 3.4.2. This view requires consideration in a capable prediction system.

Figure 5.1 is a generalisation from the specific events associated with evacuation to consider patterns of behaviour that characterise the evacuation thought processes. The system dynamics environment requires investigation of how one or more variables of interest changes over time. The square boxes are activities or process, the curved rectangles convey data or articles. The aims are to optimise the parameter ASET – RSET to be greater than 1.

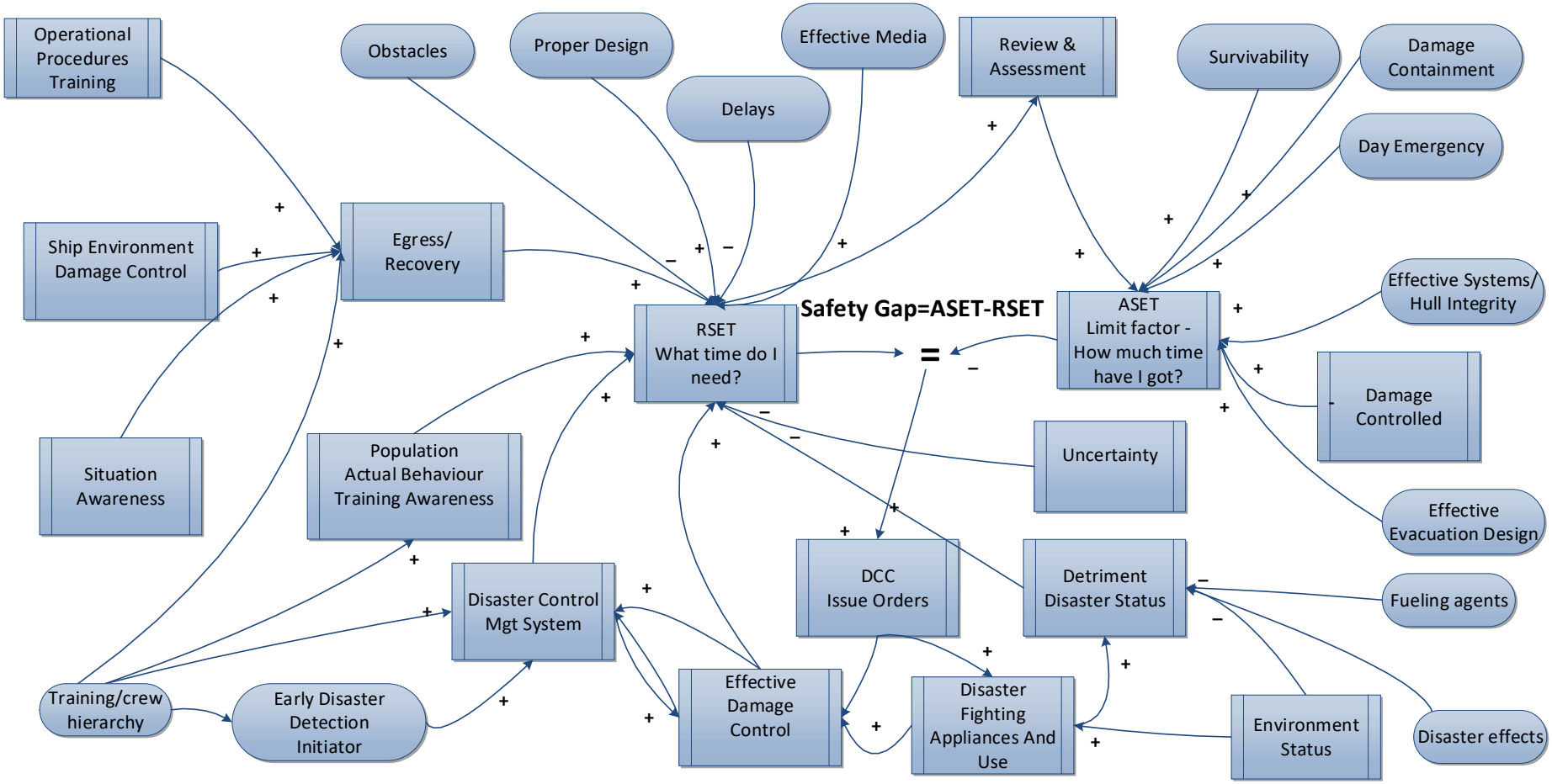


Figure 5.1 Disaster Interaction Complexity

5.3 Tying the Unknowns – the Emergency Crisis Triangle

The time for evacuation is related to the time it takes to traverse the escape route from danger areas to safe areas. This time is significantly affected by situation awareness, as shown in Chapter 4. But what is the related context of situation awareness, what is the performance metric and what principles are needed to put this into practice?

Three variables are modelled as impacts to the safety outcomes and governed by the limiting parameter ASET, which is simulated by the area within the emergency crisis triangle (ECT) see Figure 5.2. This area corresponds to the squared value of ASET which defines the available safe egress time in seconds^2. This is ideally described as the time for conditions to become untenable leading to a fatal event, like ship sinking for example. To achieve an acceptable outcome for evacuation, the predicted egress time to traverse the path to a safe condition is known as the Required Safe Egress Time (RSET). A safe outcome is that the condition ASET minus RSET is a positive value.

This triangle finds a compromise between RSET and situation awareness, or in this case, the sum of location awareness and capability (ability, knowledge, and experience). Situation awareness is the trait that uses a person's sensory system to scan the local environment to find threats in the present, and projects these threats into positive action into the future to assure safety of flight. Capability application is based on the degree that personnel can control the situation and are prepared to evacuate to enhance survivability. Key factors influencing capability of knowledge are decision making competency (Browne, Veitch, Taylor, Smith, & Smith , 2021).

The three parameters are modelled as edges and are connected, as shown in Figure 5.2. The edge (length) signifies a direct relationship and its strength. If one parameter reduces or increases, the other two parameters need to increase or decrease for the squared value of ASET (area) to remain constant. As the ASET is represented by time (s^2), the three relations are represented by time (s).

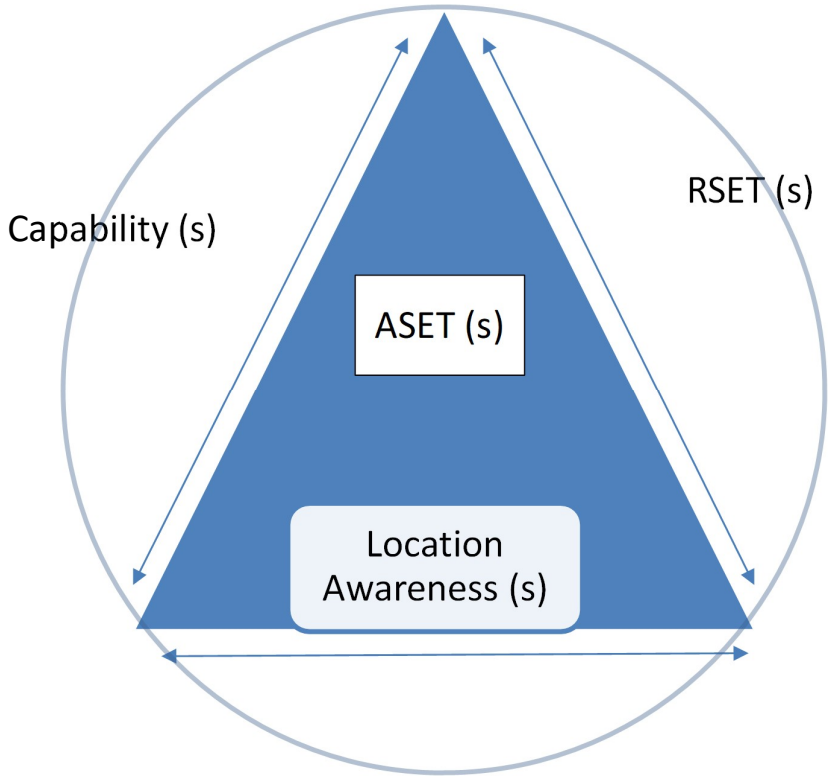


Figure 5.2 Emergency Crisis Triangle (ECT)

As the square root of the area is assumed to be ASET, the areas are represented by Heron's formula:

$$Area = ASET^2 = \sqrt{s(s-LA) * (s-CK) * (s-RSET)} \quad \text{(Eq 5.1)}$$

where,

"s" is the semi-perimeter, defined as

$$s = (LA + CK + RSET)/2 \quad \text{(Eq 5.2)}$$

LA—is Location Awareness (seconds), CK is Capability (Knowledge and Experience) (seconds).

The constraints are:

$$ASET, s > 0 \quad \text{(Eq 5.3)}$$

$$s - LA, s - CK, s - RSET > 0 \quad \text{(Eq 5.4)}$$

and,

$$ASET(ext - rad) - RSET > 0 \quad \text{(Eq 5.5)}$$

$$Situation\ Awareness = LA + CK \quad \text{(Eq 5.6)}$$

By applying the constraints and maintaining ASET as a constant, optimisation can be achieved for the relationship strength (length of triangle sides), being advantage or disadvantage in seconds.

As an example of Equations 5.1 to 5.5, optimisation was conducted. To undertake the optimisation, an added assumption was made, which relates not only the size, but also describe direction as well, similar to a vector representation. The reasoning for this is that the same vector can take several directions (application focus). This focus relates to *how* situation awareness is applied, for example, training can find situation awareness, but under what circumstances in the evacuation path is this most important? Similarly, where does instinct take control and how is this conveyed during training? Because of the direction issues, these vectors rotate within an external circle with its own external radius, showing the range of probable values. This assumption allows the constraint condition described by Equation 5.5 to be met. The optimisation shows that the best triangle shape for this problem is best described as an equilateral triangle, where each vector is equal in strength. Therefore, how is situation awareness taught? What are the constraints and opportunities to enhance this?

A study on situational awareness and its impact on emergency evacuations (Bishop, He, & Magrabi, 2018) found that the program had a positive impact with the inclusion of situation awareness training. The inclusion of situation awareness led to a positive outcome for fire wardens in pre-movement times tests conducted in 2015. Those same tests were conducted after situation awareness training had been conducted in 2016 and evacuation response times were halved. This result shows a strong influence on evacuation and has a direct correlation to ASET.

Based on the optimisation work showed above, the value for RSET for a standard evacuee equates to:

$$RSET_{safe\ outcome} = a \times RSET_{\ path\ traverse} \pm b \times RSET_{LA} \pm c \times RSET\ CK_{CK}$$

(Eq 5.7)

Where *a, b* and *c* are equal in strength.

The parameters LA and CK can be practically linked to existing data. For example, the circular MSC.1/Circ. 1533 (IMO, 2016) supplies movement data of different passenger categories. A sign of how Eqn. 5.7 can be applied is to assume that $RSET_{CK}$ is the difference between maximum Crew flat terrain velocity (1.85m/s) and the mean Passenger flat terrain velocity (1.36m/s), this ideally showing the difference between a fully aware and capable evacuee compared to a standard evacuee. This difference equates to a percentage advantage of 35% over the standard evacuee.

Evacuee performance has a limit to which he/she can undertake. The limit is described as the untenability limit, which relates to the presence to danger, like smoke or heat and exceeds pre-established tenability criteria, defining the limit.

For example, tenability criteria for deciding ASET may include the call to abandon ship or for a specific fire state (Society of Fire Protection Engineers, 2016). the visibility limit must remain between 5 and10 m or that the temperature must remain below 65° C, and that the fire extinction coefficient still is below 0.15/m for Navy ships (for known routes). These same limits can apply to commercial shipping.

Situation awareness is also linked to physical systems onboard, such as media systems which define the level of media system needed to foster the level of safety knowledge evacuees must make effective decisions. Broad categories have been defined (Brumley, 2002) in decreasing order of effectiveness:

1 Persons should have Regular/Repeated Training – This is ideal/best safety knowledge.
2 Persons should practice and conduct drills supplemented with notices – This is very good safety knowledge.
3 Announcements with distributions of pamphlets and notices should be heard – This is good safety knowledge.
4 Announcement/Notices: Inside Only – This is moderate safety knowledge.
5 Just notices – This is poor safety knowledge.
6 Limited data on movement/obstructions in an emergency. Methods assume crew moving unhindered without any blockage through primary routes.

The emergency crisis triangle presents a way of thinking about relationships between the evacuation parameters. What is important is that RSET and ASET parameters change

dynamically together as the emergency unfolds presenting a more complex view of thinking of about the problem. Prediction will need to consider these aspects. A simplified approach that can be engaged dynamically, is changing and requires updating as the parameters change.

5.4 How Networks Perform – the Application of Graph Theory

Networks have certain properties that aid the interpretation of flow behaviour (Hevey, 2018). For example, are certain vertices, and hence, spaces more important (central) than others in the nodal network? Is the global structure dense or sparse? Does it have strong clusters of vertices (path congestion) or are the vertices (paths) isolated?

The case for using Network Theory has been presented by Rigterink (2014) (Rigterink, Methods for Analyzing Early Stage Naval Disributed Systems Design, Employing Simplex, Multislice, and Multiples Networks, 2014) because it promotes the study of the pattern of interactions and connections between components of a holistically developed system. Networks can be implemented across a diverse range of objects or systems and cover technological, social, informational, and biological domains.

The networks covered in this research can be described as simple because the vertices and edges cover a specific type of entity and connection, in this case, vertices define compartments and routes on ships. The two most basic types of networks are the directed and undirected networks. In other words, the topology is either directed towards a specific outcome, like a mustering station, or can be undirected in the case of a traffic network where the topology has source vertices and final vertices that are interchangeable. Networks can also show weighted characteristics where links or edges show a preference outcome, like a traffic network which assigns weights by the number of traffic lights on a route. In the case of Navy layouts, weighted characteristics could be assigned to a-priori route which have been considered safer and more efficient to use.

Networks have the following properties that are meaningful to the instance of a maritime vessel ship (Hevey, 2018):

1 **Degree Centrality** – The degree centrality is defined as the number of connections incident to the vertex and infers that importance of the vertex in terms of space connectivity; a vertex with a high degree is considered more influential to a network

structure than a vertex with a low degree. In a ship layout, this vertex would show the space which would exhibit the maximum number traverses.

2 **Density** – Graph density is expressed as the average degree over all the vertices in a network (Rigterink, 2014). A denser network suggests a more connected network. In the case of a ship layout, optimising this parameter would ensure evacuees have real and positive path alternatives.

More information relates to vertices with many weak connections (high degree) which may not be 'central' to the network as one that has fewer but stronger connections. The degree distribution over all the vertices of a network can be used to quickly judge the robustness of the said network to both random failures and enveloping incapacities.

3 **Closeness Centrality** – The closeness index quantifies the vertices relationship to all other vertices in the network by considering the indirect connections from a node. In this case, other spaces in the ship's layout might supply more direct alternative routes.

4 **Betweenness Centrality** – The betweenness index supplies information on how important a vertex is the average pathway between other pairs of vertices. A vertex can play a key role in the network if it often lies on the shortest path between two other vertices, and it is important in the connection that the other vertices have between them. For ship layouts, this may be the key to optimising egress time.

5 **Clustering** – Clustering is the extent to which a node is part of a cluster of vertices which can be estimated. The local clustering coefficient C is the proportion of edges that exist between the neighbours of a particular node compared to the total number of possible edges between neighbours.

6 **Eigenvector Centrality** – The eigenvector centrality network metric takes into consideration not only how many connections a vertex has (i.e., its degree), but also the centrality of the vertices that it is connected to. Intuitively, it considers not just how many vertices are available, but also which connected vertices have high connectivity. Connectivity plays a part to the Navy passenger who is on a predetermined path but also knows which other important paths are available.

7 **Page Rank Centrality** – The PageRank centrality metric is best known as the core metric behind Google's search engine. PageRank ranks the node in accordance with their specific importance in the directed network, as it measures:

a. The number of vertices that link to the target

b. The PageRank centrality of the linking vertices
c. The link propensity of the linking vertex.

This research uses the above network (ship geometry) characteristics in an alternative and novel means to aid the Navy ship layout design effort and develop the flow behaviour in the evacuation process by finding path performance metrics.

The important aspect is that it defines the relationships in the Network and can be a useful tool for defining situational awareness.

5.5 Path Optimisation

The benefit of representing networks as graphs is that graphs can be signified by linear programming mathematics, being considered a special case of programming. The canonical or standard form is the usual form of describing a linear programming problem, as an equation with upper and lower constraints, such as:

$$f(x1, x2) = c1x1 + c2x2 \leq b1$$

A network forming vertices and edges has many solutions and hence, one may optimise the flow to correspond to minimising a cost (time) or a capacity (people density). This research focused on deciding the one set of paths that corresponded to minimal time needed for traversal. For a minimum time, flow problem with n vertices:

x_{ij} = Number of evacuees traversing from vertices $_{i\ to\ j}$ using edge $_{i-j}$ (MIT, 2013)

$$\sum_j x_{ij} - \sum_k x_{ki} = b_i \quad (i = 1, 2, \ldots, n), \qquad \text{[Flow balance]}$$

$$l_{ij} \leq x_{ij} \leq u_{ij}. \qquad \text{[Flow capacities]}$$

Eqns. (5.8)

With many publications in the field, the logistics fraternity has labelled their use of linear programming for production, inventory and demand problem as ‘multi-commodity’ (MC) modelling and is now considered a universal approach that can also be adaptable to many industrial problems (MIT, 2013).

During emergencies on a ship, evacuees have evacuation maps posted in rooms and other selected areas onboard as placards. Each map shows the location of the current area and the path to the nearest exit. The purpose of these maps is awareness of a route out, thereby assuming a shortest path. However, the shortest path does not consider the flow density – flow relationship, which means the higher the density, the higher the egress time. The shortest path configuration on the placard does not lead to minimum egress time for large densities, as those found on ships (Proceso & Teknomo, 2012). The research in Proceso and Teknomo's paper focused on using a network approach for crowded pedestrians using agents.

Not only is passenger density a factor, but the travel speed of the evacuee is also a function of many factors (variables) such as age, training, fitness, mental capacity, together with area widths, lengths, obstacles, lighting, gases, ship motion and flooding, for example. These factors in fact consist of a set of constraints and limitations to negotiate a safe path.

Therefore, given a ship's geometry and topology, the requirement is to decide the optimum path choice to egress safely. Optimisation is key to deciding the effectiveness of evacuation planning.

5.6 Ship Evacuation Representation on a Canvas

Using the network approach, the model in this research presents the intermediate framework, a 'mesoscopic' view of the ship's environment which is represented by a graph G = (V, E), where V is the set of vertices (nodes), each representing critical areas such as compartments, corridors, doors (if this level of detail is required), start points or end points, stairs, elevators, escalators and ramps. E is the set of edges (links), each being a direct path or link from one node to another.

Figure 5.3 illustrates a simple canvas from Proceso and Teknomo (2012) that shows a sample room layout with the corresponding network graph structure. The blue vertices denote source vertices, the brown ones denote sinks. The canvas is vital as a visual tool to understanding the topology and the path constraints.

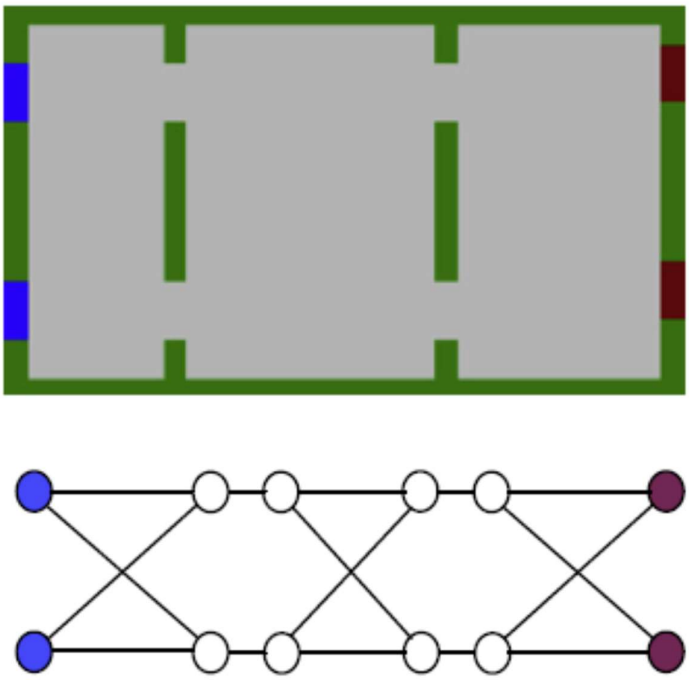


Figure 5.3 Sample Floor Canvas and Corresponding Vertices in a Graph Representation (Proceso & Teknomo, 2012).

Using conventional thinking, each edge has an equivalent length and an equivalent width, effectively limiting the maximum number of persons that can simultaneously occupy the space represented by the edge. Limits are area capacity of the given edge. Doors have width dimensions only in this method.

The approach can be simplified and changed to reduce the geometrical complexity. All spaces and doors are vertices. Edges are notional interface points like doors, which have no widths, corridor transitions and the like. Interfaces transitions are manifested as a flow correction or disruption.

Figure 5.3 illustrates an alternative view of the network. Vertices occupy spaces/areas and edges only find relationships, interactions, or connectivity. In this representation, one can reduce the number of vertices from twelve (12) to eleven (11). This simplification is based on what information edges convey about the direction and strength of the relationship between the vertices. Edges can be either weighted or unweighted. A weighted edge reflects the strength of the relationship between vertices by varying the thickness and colour density of the edge connecting the vertices, with thicker denser coloured lines showing stronger relationships. Such a technique is used to decide the number of persons transgressing the edge (path). The edge may be unweighted and simply

represent the presence or absence of a connection. The absence of a relationship results in the vertices not having a connecting edge, and therefore no possible path to traverse.

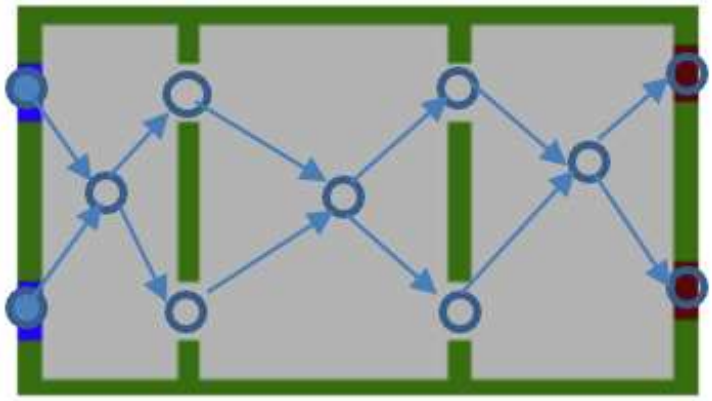


Figure 5.4 Mesoscale Modelling Scheme for this Research

Directed networks can be causal structures that follow a directional end point. All the variables that have a causal effect are measured in the network (Hevey, 2018). In modelling of ships, there is reason to apply a directional behaviour to gain the advantage of a safe path aim and to optimise the efficiency of the algorithms. However, one can include bi-directional edges to model contra flow or alternative pathways by doubling back, should constraints which evolve require it.

To define the canvas, various node display tools exist that supply the visual field from which to work on. A significant amount of private and open-source network plotting software is available as open source, (Devendra, 2015). To plot the network, the vertices and edges need to be positioned in a manner that reflects the patterns of relationships present in the data. The most often used approach in psychological networks is the Fruchterman-Reingold algorithm (Fruchterman & Reingold, 1991) which is a force-directed algorithm that tries to minimise edge crossings.

For Navy purposes, two algorithms that provide the best viewing for inspection purposes are the Harel-Koren Fast Multiscale Layout (Aldahdouh & Aldahdouh, 2019), and the Sugiyama Layout options (Sugiyama, Tagawa,, & Mitsuhiko, 1981). These options supply versatile means to consider the ship's layout. These layouts follow a layered graph drawing or hierarchical graph drawing in which the vertices of the ship's directed graph

are horizontal rows or layers with the edges generally directed downwards, as per as Sugiyama-style graph (Sugiyama, et al., 1981). It does this by minimising edge crossings by arranging the vertices in layers, as per Sukiyama style (Sugiyama, Tagawa,, & Mitsuhiko, 1981) layout showing the different layout options available.

An example of the development of different network layouts is taken from the analysis of the *SS Caledonia* (Marian & Capizzi , 2020). This analysis used NodeXL, an add-in for Microsoft® Excel® illustrating and comparing the different layout algorithms (see Figures 5.5 to 5.9). The *SS Caledonia* forms four decks in total and lends itself to network modelling.

Layouts do not reflect actual geometry but show network connectivity only. The algorithms presented in Figure 5.6 to Figure 5.9 show layout view options of network connectivity to better understand embedded relationships. The best view is dependent on the engineer's task and which details are needed. Views can change instantly and are dependent on what details are needed. For the purposes of this example, the Sukiyama scheme portrays an easier understanding of the ship's deck layout.

This example shows the benefits gained through the examination of network layouts through the lens of a world view. It is very useful to switch between view to get a better understanding of the solution space.



Figure 5.5 *SS Caledonia*

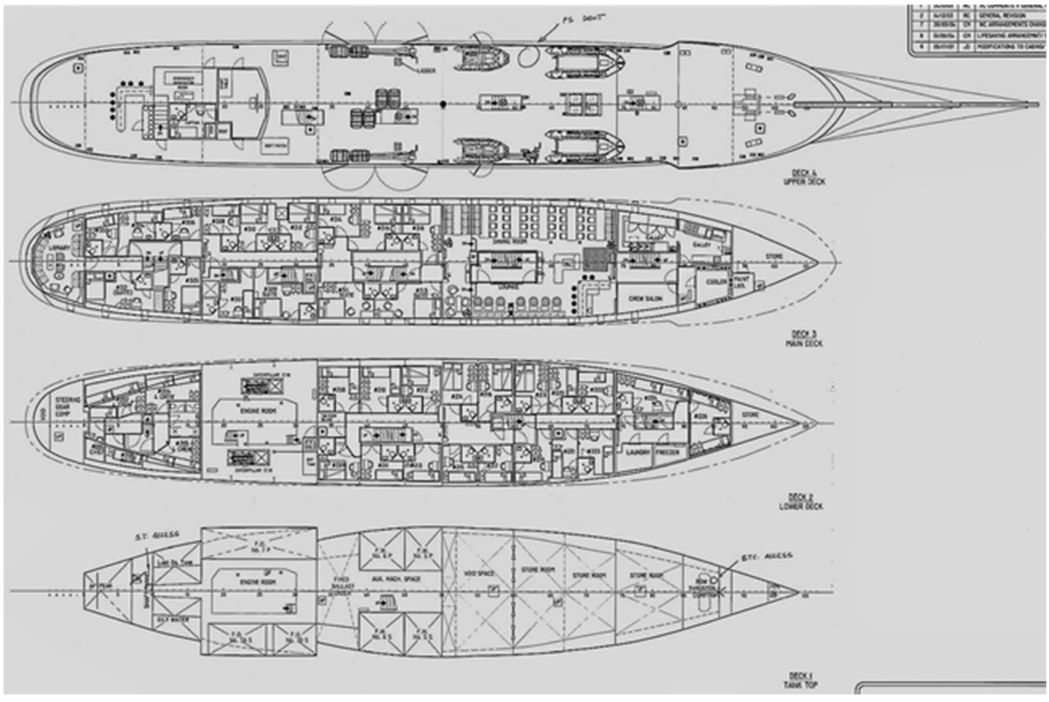


Figure 5.6 SS Caledonia Deck Plan

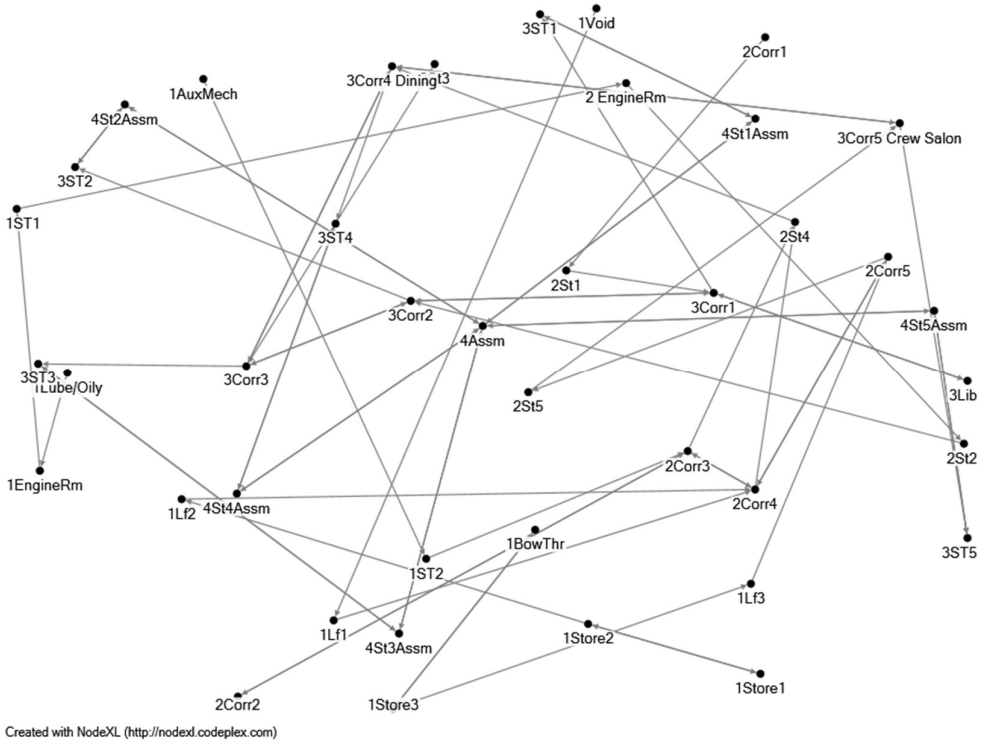


Figure 5.7 Fruchterman-Reingold Layout algorithm

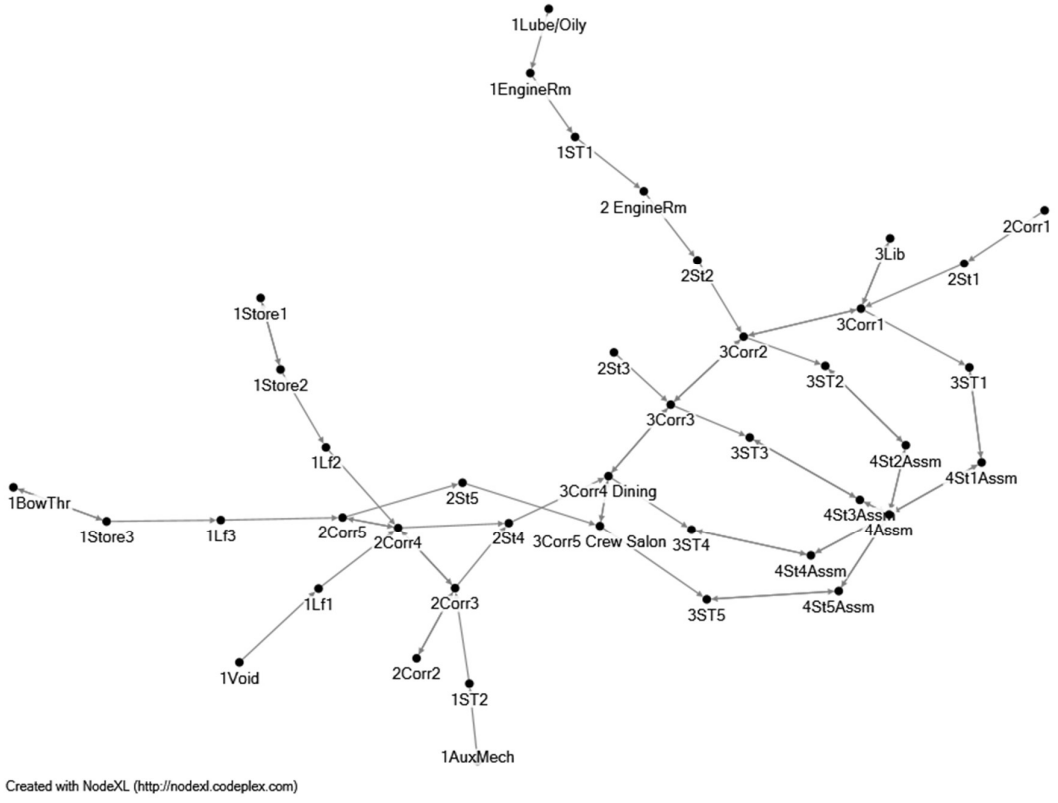


Figure 5.8 Harel-Koren Fast Multiscale Layout Algorithm

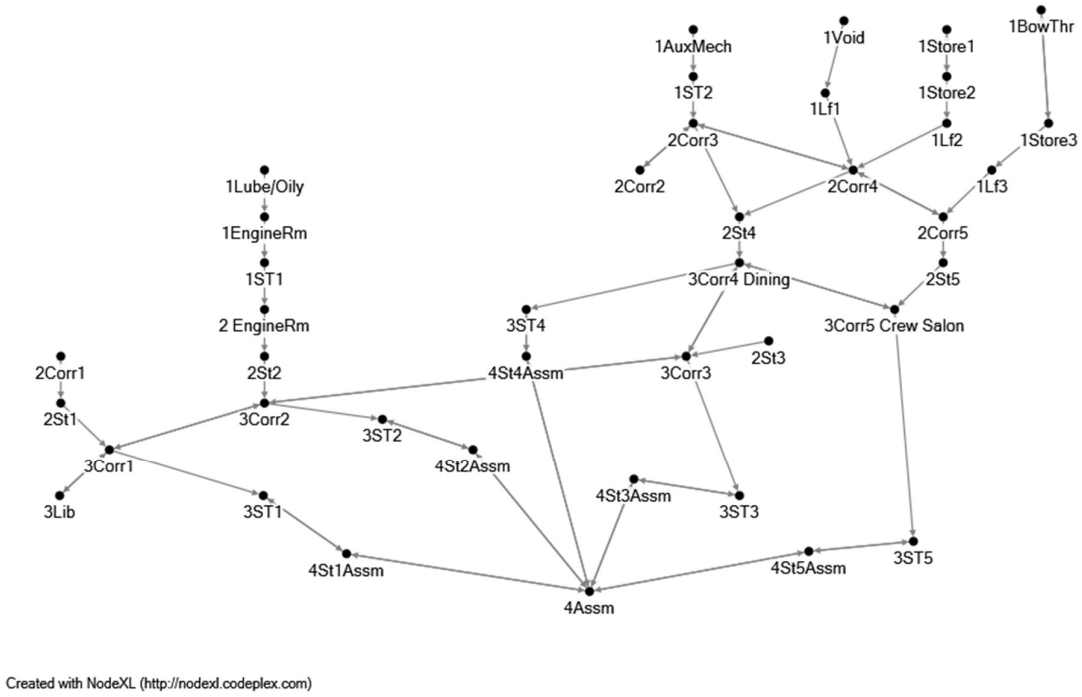


Figure 5.9 Sugiyama Layout Algorithm

NodeXL was chosen for the case study used in this research and is an add-in for Microsoft® Excel® making it *considerably* useful and versatile for MS Excel analysis. It enhances the capability of viewing network topologies by content analysis of structure and relationships. NodeXL uses a hands-on approach and assumes no knowledge of network analysis. It is an efficient visual tool that supplies clear view of the vertex topology and its edges and supplies the means to easily analyse the Network specifics. NodeXL is Open-Source software (Socialmedia Research Foundation, 2020).

5.7 Hydraulic Flow Supports Simulation

Hydraulic models are based on the Society of Protection Engineers guidelines, (Society of Fire Protection Engineers, 2016). Simple flow is constrained by a boundary and described by a set of equations. The evacuation time (i.e., the time predicted by the hydraulic model) utilises a series of expressions that relate data acquired from tests and observations to a 'quasi' hydraulic model of human flow. These primarily relate to the following considerations: effective width, population density, speed, flow characteristics, time for passage through a component, and transitions between components. Evacuees flow from vertex to vertex (e.g., from a corridor to a stairwell), with movement speed

dictated by the flow equations that form the model (Gwynne & Rosenbaum, 2016) and path constraints.

5.8 Movement Velocities

The approach used for estimating evacuation traffic delay is to use the hydraulic analogy, a process by which traffic is simulated as abstract flows using people movement velocity. Another approach considers the behavioural aspects of the people to decide movement speed. Prerequisites for either of these approaches are based on the availability of information/data on the people movement, such as speed, rate of travel along a corridor, ramp, and/or stairs. Figure 5.10 and Figure 5.13 Reported Average Speeds which is used to inform the people movement speeds for density (people per square metre) or age (years) used for determining egress time.

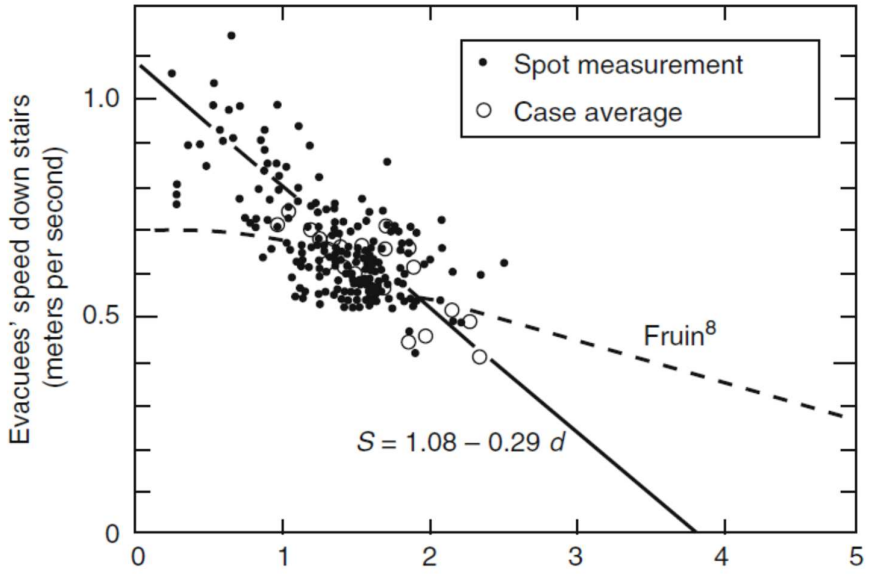


Figure 5.10 Typical Speed Versus Density Data ((Society of Fire Protection Engineers, 2019))

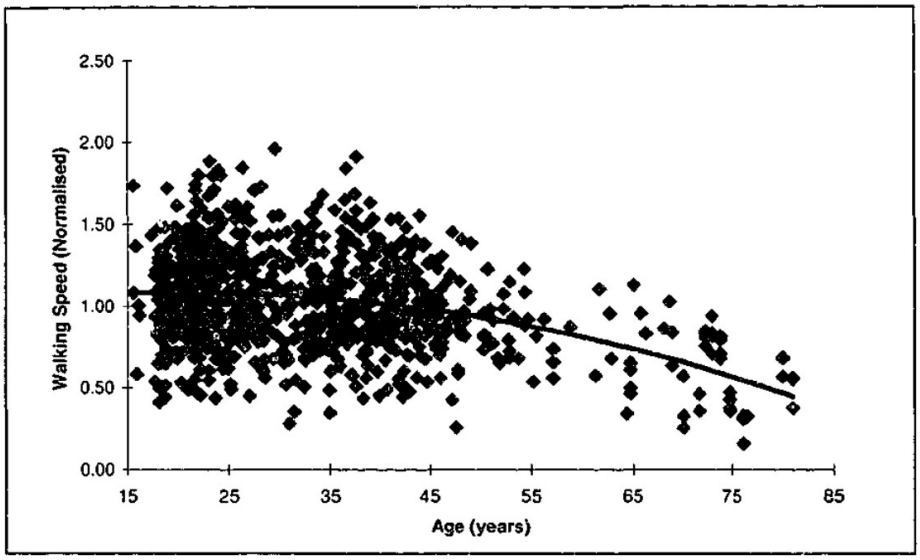


Figure 5.11 Person Age and Walking Velocity (Brumley, 2002)

Figure 5.12 shows the spread of data, up to a 0.3 m/s spread on the state of uneasiness of the individual person's performance. It is noted that over 47% of the population will suffer some sort of disturbance.

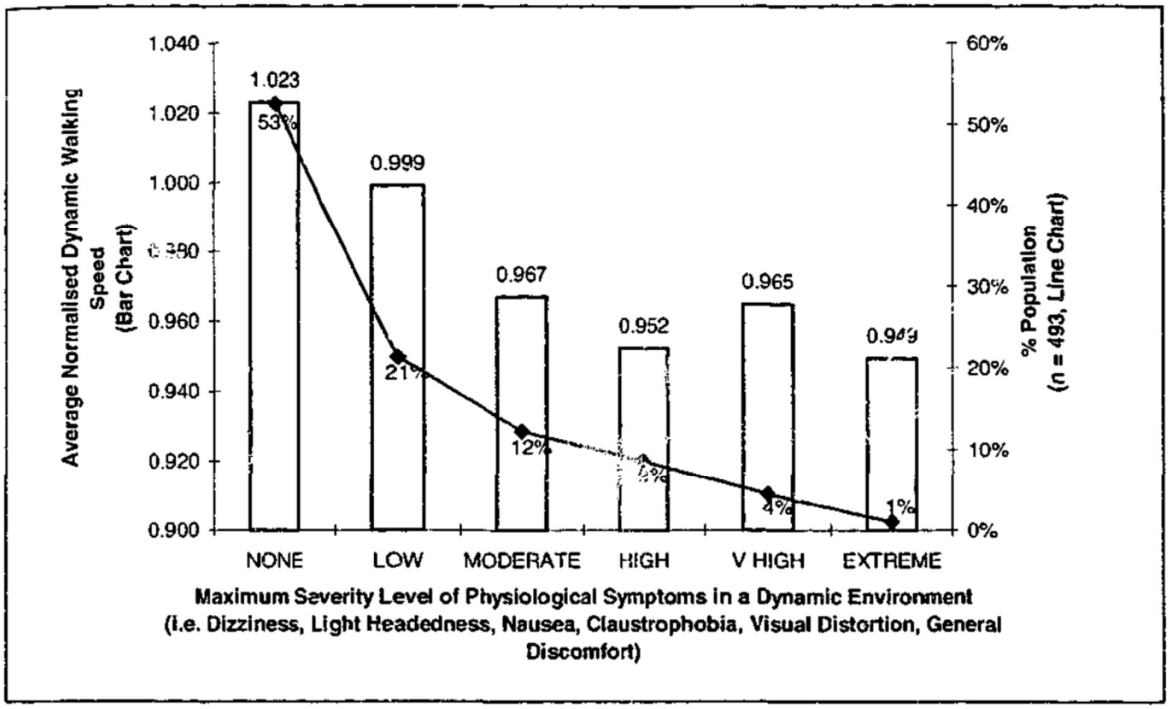


Figure 5.12 Physiological Symptoms in a Dynamic Environment (Brumley, 2002)

Although walking velocity was not included in the velocity determination in the case study presented in Chapter 7, it can be used in the velocity calculations to influence and affect to the overall result. However, for the case study, movement velocity was extracted from Figure 5.13. This velocity baseline supplied the data needed to conduct the stochastic analysis. The mean and standard deviation was decided from this data.

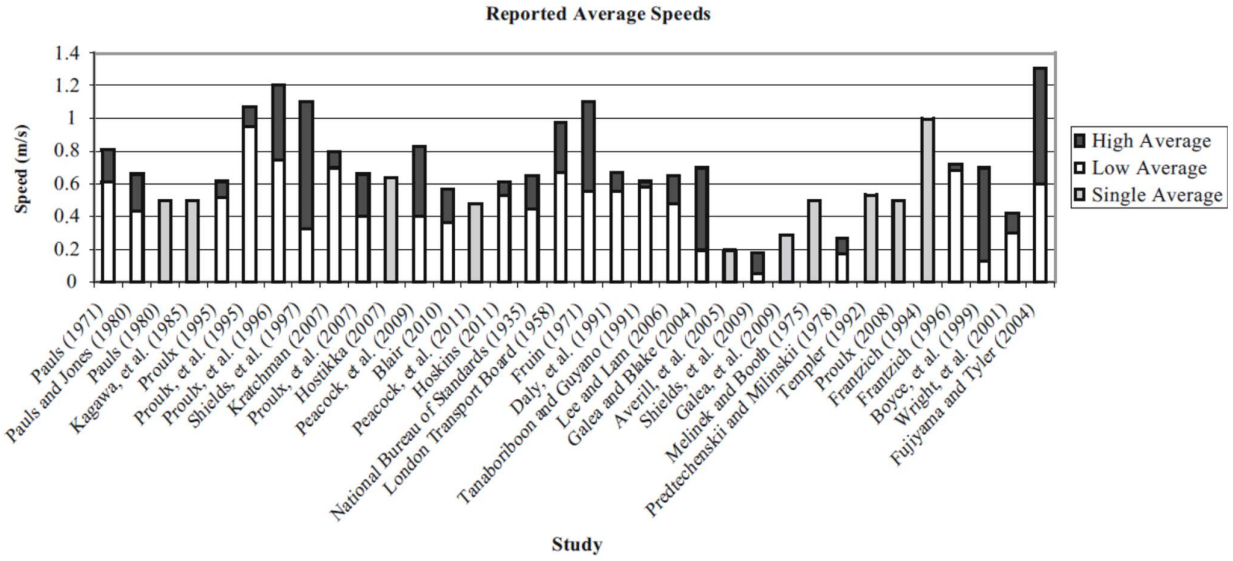


Figure 5.13 Reported Average Speeds (SFPE Task Group , 2019)

People movement is the concept of movement speed with effective path width, the number of persons moving past a point in the evacuation route per unit time per unit distance of effective width can be decided. Termed ‘Specific Flow’, it is calculated as the speed multiplied by the density of the population. This criterion sets up the limits of people movement and is a means to optimise spaces or areas in the ship’s topology.

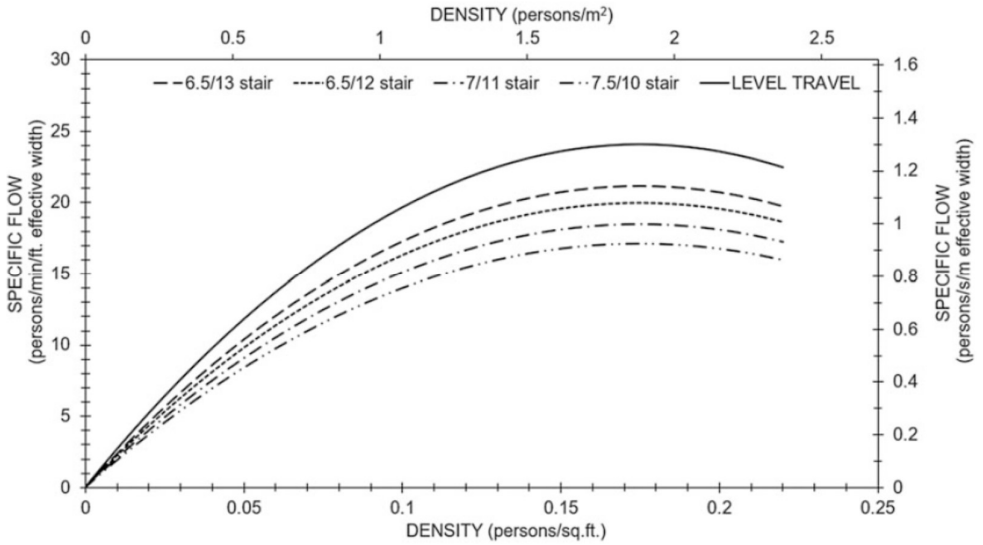


Figure 5.14 Specific Flow as a function of People Density (Society of Fire Protection Engineers, 2019).

Figure 5.14 is useful in the sense that it applies constraints to the movement based on the people density. Constraints are used in the hydraulic model as the upper bound of people flow in the movement calculations. The Figure shows a maximum value of specific flow at approximately 1.3 persons/s/metre (width).

An alternative view (Brumley, 2002) specifies that Velocity is a function of the following parameters:

1 Capsize list
2 Age
3 Gender
4 Congestion
5 Infant characteristics
6 Sea sickness
7 Performance factors.

Each parameter is defined and specified with empirical technical data. When presented as a holistic data set, the technical method is simplified by combining various parameters associated with flow properties within defined bounds.

5.9 Concluding Remarks

This chapter informs the analysis “pieces” that make up the framework for solving the research problem and the specific processes used to determine an approach to find a solution to the most efficient and timely path selection for evacuees. It is based on existing research and well-known network analyses techniques, namely multi-commodity, and network theory approaches, and common industry data. The advantages of network systems approach are as follows:

1 Simple to construct and to audit
2 Simple to change and/or optimise
3 Simple to impose constraints such as obstructions, restricted access, flow constrictions
4 Research data is the form that can be readily applied to network models.

The research approach is novel in the way it implements the framework using proven analysis techniques and off the shelf software such as MS Excel, which is a widely available application. It is efficient and user-friendly making it available to a larger technical audience.

The importance of movement of velocity has been explained finding the type of data used and an example source of the data. Different data types that can be considered depending on the application context.

Chapter 6 Evacuation Modelling Standard

6.1 Introduction

This chapter finds several evacuation structures that are used to decide, in the design case, policies and guidelines that support the assessment of whether the evacuation prediction solution can deliver a possible outcome and the requirements for delivery. In most cases, analysis is linked to safety at sea and understanding the full extent of this and the issues with compliance to the rules, how the frameworks work on the principle of using a goal structure notation framework which puts forward an argument for safety but needs to be provided with objective quality evidence that substantiates the argument. It works mutually with the techniques found from the earlier chapters. The description of the standards and related articles to the framework are presented in this Chapter.

6.2 Maritime Standards

The International Maritime Organisation (IMO) has released standards in relation to safe evacuation for onboard systems and services for passenger ships to remain operational in the case of an emergency for the safe return to port (IMO, 2006). MSC.1/Circ. 1214 presents a description of the systems and services that need to be considered during evacuation to ensure the ship has the required design layout considerations built-in to the design of the ship. It supplies an understanding of evacuee's risk in achieving a safe evacuation and the risk to reaching a safe port. The implementation of this Standard decreases the risk to evacuation performance as it increases the ASET time giving more time for the evacuee to egress.

As a minimum, the following facilities are needed for a vessel to gain operational release (IMO, 2006):

1 Fire main system – In case of fire, the fire main should remain operational in all main vertical zones not directly affected by the casualty. Water for fire-fighting purposes should be available to all areas of the ship.

2 Internal communications systems – A communication means should be available for supplying orders to firefighting and damage control teams and personnel in charge of evacuation and abandonment.

3 External communications – The ship should be capable of communicating via the Global Maritime Distress and Safety System (GDMSS) which connects coast stations

and vessels via satellite and radio communications when at sea, or if the main GMDSS equipment is lost via the Very High Frequency (VHF) Marine and AirBand distress frequencies. Marine VHF radios provide (handheld) back up to ship-to-shore communications.

4 Bilge system – The bilge pumping system and all associated equipment essential for its operation should be available in all spaces not directly affected by the casualty.

5 Ship's power for damage control and abandonment – Electrical power should be available for the abandonment of the ship, including life-saving appliances and arrangements and the systems referred to in the Safety of Life at Sea (SOLAS) regulation II-2/22.3.1, with due regard being paid to such services as may be worked simultaneously.

These required facilities affect the ship's safety after a casualty at sea and need to be considered in an evacuation framework. These requirements become assumptions to design which are needed to supply a correct and efficient analysis. Effort is required as to the efficacy of these facilities and how they affect emergencies when needed.

The evacuation framework needs to also consider the technical data related to movement of a ship. A comprehensive set of technical data and examples on the movement behaviour has been provided in a comprehensive PhD thesis on human performance during the evacuation of passenger ships (Brumley, 2002).

This technical data is tailored to suit the individual ship design:

1 Run Flexibility – allows for the alteration of general input factors, such as ship's data and passenger data which affect ASET – the time for the emergency to become untenable
2 Safety – allows for the alteration of evacuation route choice based on safety media and experience. For real time sensing, media information and data affect the movement of evacuees based on the strength of the evacuation communications transfer. For design, a factor needs to be included to show the effect on movement due to poor, adequate and good communications systems
3 Motions – should allow for the alteration of vessel motions. This is not a factor for real time mentoring but should be considered in the movement studies for design.
4 Occupants – allows for the alteration of vessel layout and population distribution

Brumley's (2002) research also describes performance criteria which supplies a technical data compendium for this research.

6.3 The Important Safety Standard ANEP 77

The Allied Naval Engineering Publication ANEP-77, Naval Ship Code (NSC) (NATO, 2017) supplies a standard for Navy surface ship safety based on and benchmarked against IMO conventions and resolutions that embraces the majority of ships operated by Navies. The code adopts a goal-based approach. The principle of a goal-based approach is that the goals should represent the top tiers of the framework, against which a ship is verified both at design and construction stages, and during ship operation (see Figure 6.1).

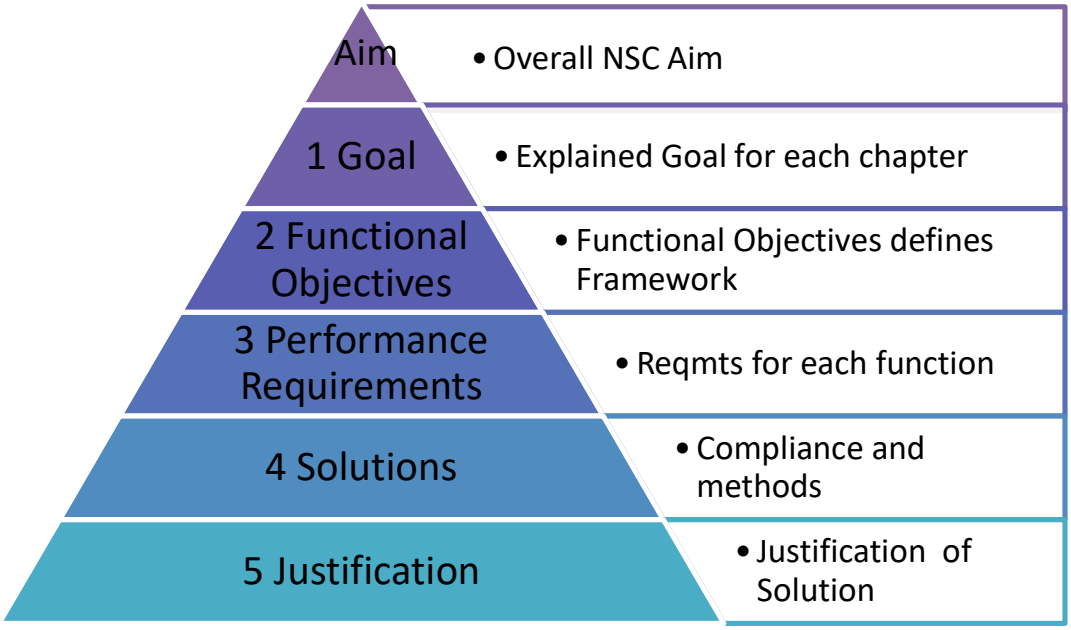


Figure 6.1 ANEP 77 Structure

NSC arrangements for escape, evacuation and rescue of personnel shall be designed, constructed, and kept supplying an effective:

1 escape for all embarked persons from all manned spaces to a place of safety if foreseeable accidents and emergencies at least until the threat has receded.
2 means of evacuation from the ship
3 means of recovering persons from the sea,

The NSC lists detailed requirements for performance:

1 Evacuation time of the undamaged vessel does not exceed 30 minutes

2 The joint Escape and Evacuation time of the undamaged vessel does not exceed:
   a. 60 minutes for vessels with vehicle Roll On/Roll Off (RO-RO) spaces
   b. 60 minutes for vessels with less than three main vertical fire zones
   c. 80 minutes for all other vessels.

These performance standards are similar in context to those regulations of the IMO and add weight to the approach said in MSC.1/Circ. 1533.

The NSC specifically says that an evacuation prediction analysis shall:

1 Optimise the effectiveness of escape and evacuation measures, considering:
   a. normal seagoing conditions
   b. damaged conditions defined in the Concept of Operations Statement.
2 Represent flows of persons during escape and evacuation as factually correct as possible.

The maritime industry has adopted these performance standards as a basis for analysis and demonstration for design applications and as a basis for acceptance of a newly acquired vessel.

6.4 The Design Context

A case study has been chosen to compare the outputs of MSC.1/Circ. 1533 Guidelines with the outputs generated by the evacuation framework developed in this Chapter. This evacuation framework finds a performance standard which can be used in the design context, when comparing designs. It provides a first design method to enable an illustration of the techniques and processes developed earlier. In this instance, guidelines use as an example the application to RO-RO ships. These examples can also be used in the Navy context. However, the guidelines should not be viewed as comprehensive and complete analyses, nor as a sign of the relevancy of the data used. Other classes of ships require the standard to be specific to that specific ship class.

The case study data detailed in Chapter 7 is used in preference to real time movement data to confirm the research method. It assumes that future implementations of Real Time Location Systems (RTLSs) will be used in a similar manner, albeit in real time. The case study refers to an early design analysis of arrangements of a hypothetical new ferry ship.

MSC.1/Circ. 1533 Guidelines assume a performance standard of 60 minutes, the same as typically used for the RO-RO passenger ships in existence.

This research considers aspects which have not been covered in MSC.1/Circ. 1533 which refer to benefits of adopting the proposed evacuation framework.

6.5 Performance Standards

The SOLAS Regulation II-2/28-1.3 provides another set of guidelines for the evacuation of passenger ships and high-speed passenger craft (Dongkon et al., 2003). It is compared to MSC.1/Circ. 1533 (IMO, 2016) which presents both simplified and advanced methods to analyse evacuation by using typical benchmark evacuation scenarios and relevant data to decide evacuation performance of roll on/roll off (RO-RO) and other ships. MSC.1/Circ. 1533 is the latest revision in a series of similar guidelines.

Most data and parameters stated in the SOLAS guidelines are based on well-documented data originating from the civil building industry, not shipping. The evacuation analysis aims for existing or new design ships are to find congestion points and/or critical areas supplying recommendations as to where these points and critical areas are located on board. These guidelines supply performance criteria in terms of the total calculated evacuation time compared to the allowable evacuation time.

The MSC.1/Circ. 1533 evacuation performance standard is defined as:

$$1.25\ (R + T) + \frac{2}{3}(E + l) \leq n \qquad \text{(Eqn. 6.1)}$$

where,

R—is passenger response duration – for purposes of showing a benchmark, R should be 10 minutes for night-time scenarios and 5 minutes for day-time scenarios. R could be stochastically derived based on available data.

T—is the total travel time, calculated in seconds.

E+L—is the embarkation and launching time which is initially set to ≤ 30 minutes for this exercise based on rationale presented in MSC.1/Circ. 1533.

n for passenger ships = 60 minutes, but 80 minutes if the ship has more than three main vertical zones. A safety factor of 1.25 is applied.

A figure of merit (FOM) can be introduced to decide route effectiveness, following the performance standards:

$$FOM = (R + T + \frac{2}{3}(E = L)/n \qquad \text{(Eqn. 6.2)}$$

For this research, the focus is on deciding a Key Performance Indicator (KPI) related to T. The other parameters are assumed to be correct for simulation purposes. This research sets up the simulation framework from which to characterise evacuation, where its greatest strength is when comparing different cases.

Similarly, a second KPI can be related to path/traffic delay time, which is considered a hazard, and therefore a risk. Traffic delay time should be eliminated if possible, and if not, should be equal with the accepted level of risk during the design process. A cost/benefit ratio is performed where the cost of the design/redesign should be proportionate to the benefits of redesign blockage/choke paths.

Traffic delay is measured in time and should be somehow proportionate with the 'safe' time to egress. If, for example, the calculated time for egress with traffic delay is considered the mean value, then the traffic delay should be considered a departure from mean, part of the sample set.

To understand the risk levels associated with emergency evacuations, US Military Standard 882 (US Defence Dept., 2012) decides the level of risk associated with system safety. The probability of occurrence and the consequence are the determinants for risk. A hazard is a real or potential condition that could lead to an unplanned event or series of events resulting in death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment. For evacuation, obstacles, corridor geometry imperfections or number of people are considered hazards because they lead to traffic delay time exacerbating RSET. Based on historical data, the probability of a fatal ship occurrence is considered Improbable with a probability value of 1 x 10^{-6}. The

consequence is considered Catastrophic (at least one death). The level of system risk that an evacuation occurs is considered Medium.

To mitigate the risk associated with ship loss, total time (T) for evacuation needs to be as low as possible. An optimised T will aim to reduce the time delay due to traffic for the system to zero. This happens when the specific flow (number of persons/per second/path effective width) is below a maximum specific flow rate of 1.3 p/s.m) (see Figure 5.14).

Time for traffic delay:

$$T_d = \#Persons\ (P)\ \div Calculated\ Flow\ (Fc) \quad \text{(Eqn. 6.3)}$$

$$T_d = Fc\ \div Effective\ width\ (We) \quad \text{(Eqn. 6.4)}$$

$$2_{nd}\ KPI:\ T_d < \frac{P}{1.3 * We} \quad \text{(Eqn. 6.5)}$$

6.6 Concluding Remarks

This chapter has reviewed and assessed the tools and methods to develop the framework by considering maritime standards as the basis for maritime assurance needs. Performance standards and related articles supply a measure of the evacuation performance of a specific vessel design which supplies a standard technical aim value for design purposes. FOM and Traffic Delay KPIs have been introduced to aid design efforts when optimising evacuation studies. These can be considered KPIs for evacuation and can be used holistically, and when less detail is needed for the design of compartment/corridor widths.

While earlier chapters have confirmed the use of multi-commodity analysis through network theory, this chapter has argued that meeting a performance aim is a possible method to solve ship evacuation cases at a higher level of system design. Performance standards supply an initial systems concept on ship layout and highlights obvious design issues prior to conducting detailed prediction studies or use as a metric for the assessment of platforms.

The framework allows for a lower level of detail dependent on the model complexity and the details needed. The frameworks described are a useful to stage evacuation analysis in phases, each phase with added levels including added spaces or path irregularities.

Chapter 7 Case Study

7.1 Introduction

The process for prediction analysis is best described by a case study, which presents an integrated view of the entire process and the thoughts behind it. The case study is tailored to meet the aims of this research. Therefore, fine details have not been included in the case study, although there are sufficient details have been included to understand the processes and methods employed.

7.2 The Process to Determine Safe Evacuation

The following techniques have been used to develop the evacuation plan:

1 the approach is theoretical and mathematically focused to develop realistic ship evacuation simulations at a system level for the needs and requirement determinations in a requirements and preliminary design environment
2 the methodologies are based on building evacuation studies, and associated and requisite evacuation data
3 the simulation is based on a benchmark scenario which is not specific to cases and detailed ship configurations, or environmental issues found during an actual evacuation. In this case, the primary evacuation case is the night case aligned to the Fire Safety Systems Code (IMO, 2015) which includes a specific passenger manifest.
4 different routes are identified as groups of passengers start from a different first vertex or compartment and is modelled as a directed path. An evacuation duration is decided for each path from its source vertex to the Assembly Area
5 the path showing the longest evacuation duration is chosen as the representative duration for the evacuation
6 uncertainty in the solution is expressed by conducting a Monte Carlo analysis to find the most likely evacuation time duration (Monte Carlo typically uses up to 1000 iterations).

The Evacuation Model is made up of seven functions or sub-models. They are highlighted in Figure 7.1 in black:

1 the Input Geometry model.

2 the Visualised Plotting model (NodeXL).

3 the Path Optimisation Excel Solver®.

4 Deciding best path calculation,

5 the Hydraulic Analysis models.

6 the stochastic Monte Carlo model.

7 Path time calculation.

The approach for this model process is as follows in with the stages described in Figure 7.1.

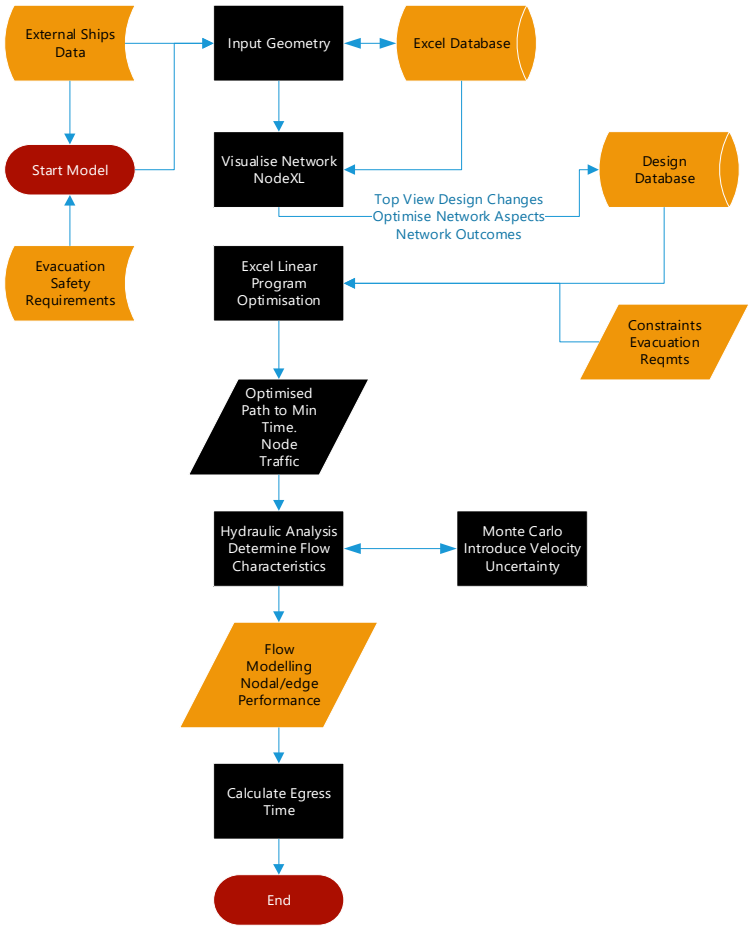


Figure 7.1 General Process for Evacuation Time

EXCEL – Input Geometry

1 Define nodal and edge topography representing ship layout using a network representation with source vertices (source) that are occupied with passengers evacuating to the final destination as the end point (sink)
2 Define node properties, traverse length, area and entry/exit passage clear widths, and the number of exits. For Naval ships, at least one exit is needed for each compartment with more exits being desirable
3 Define the person density for the space and decide constraints based on area, and length to width ratios.

NodeXL

1 Plot network to check topography layout and direction of flow. Some edges can be modelled as bi-directional which can be considered another access pathway if environmental constraints are present
2 Maximum people density ranges from 0.05 to 3.8 persons/m^2; flow velocity is a function of people density (Society of Fire Protection Engineers, 2016)
3 If the node is a stair, then an average value is used from the step riser height and tread data is presented in Table 59.2 of the Society of Fire Protection Engineers (2016).

Optimisation

1 Define constraints to optimise (to minimise travel time) – in this case, the edge capacity using the nodal flow balance criterion
2 Use Excel Solver® to decide the number of persons traversing each path (edge)
3 Use NodeXL to check for 'trodden paths'
4 Analyse vertices which are fed from more than one route using the hydraulic technique for accumulated density
5 Check evacuation performance for the total number of persons is the sum of the maximum time for each edge that has been traversed. The maximum travel or traversing speed (constraint) is defined as 1.19 m/s.

Monte Carlo Analysis and V&V

To understand uncertainty in the model data and method, use the Monte Carlo technique introduces a random variable parameter and aligns it with the mean and standard deviation of movement velocity data presented in Figure 59.4 of the Society of Fire Protection

Engineers (2019).An Excel formula is used that returns a value that represents the inverse of the normal cumulative distribution for the specified mean and standard deviation with the probability set as random (Excel Functions, 2020).

Edge properties can be changed to see how factors such as visibility, age, disability, or access affect the edge distance or traversal time.

This technique finds design issues clearly and should be considered during the design phase. The MC tool is flexible and more adept to initial evacuation ship designs quickly, or to be used to optimise existing designs.

To consider the actual conditions during evacuation such as fire, smoke, visibility and ships motion, the network model can be adapted to be individual passenger movement speed as needed. This tool provides a means to access resilient and realistic evacuation parameters.

7.3 MSC.1/Circ. 1533 Ship Information and Results

The application of the evacuation prediction method is shown as the case study. The baseline example to compare the results of the prediction assessment is the IMOs prediction in the Maritime Safety Committee (MSC) .1/Circ. 1533 for a RO-RO ship. The case study achieves the major aim to verify the case study prediction results against the MSC.1/Circ. results.

The case study also provides a better understanding of the prediction approach and the versality of multi-commodity to solve the prediction of evacuation. A typical case study of a ship normally uses all the vertical zones in a ship (i.e., two main vertical zones (in this case MVZ 1 and MVZ 2 zones) of the hypothetical RO-RO ship. For this case study the MVZ 1 zone is used with a day scenario considered, herein called Case 2 (Day) (see Figure 7.2). Case 1 is not considered any further as the single example is sufficient to assess the efficacy of the prediction method.

For Case 2 (Day), the first embarked passengers correspond to a total of 449 persons distributed and found in the crew and passengers' cabins as follows:

1. 42 passengers in Deck 5

2. 65 passengers in Deck 6 (42 in the fore part and 23 in the aft part)

3. 26 passengers in Deck 7
4. 110 in Deck 9
5. 96 passengers in Deck 10
6. 110 passengers in Deck 11
7. Deck 8 (the assembly station) is empty.

The prediction method reproduces the network representation shown in Figure 7.2, but not entirely. The difference is in the stairwell development, which is considered a mix of spaces with the main Stair C space covering all the deck levels (see Figure 7.2,with different stair spaces for connecting deck levels for the RO-RO ship.

Passengers are initially assigned to specific vertices (spaces) and are connected via edges. The process is advanced, and the final result must show that the number of passengers at all vertices at the start are present at the finish at the Assembly station with all constraints met.

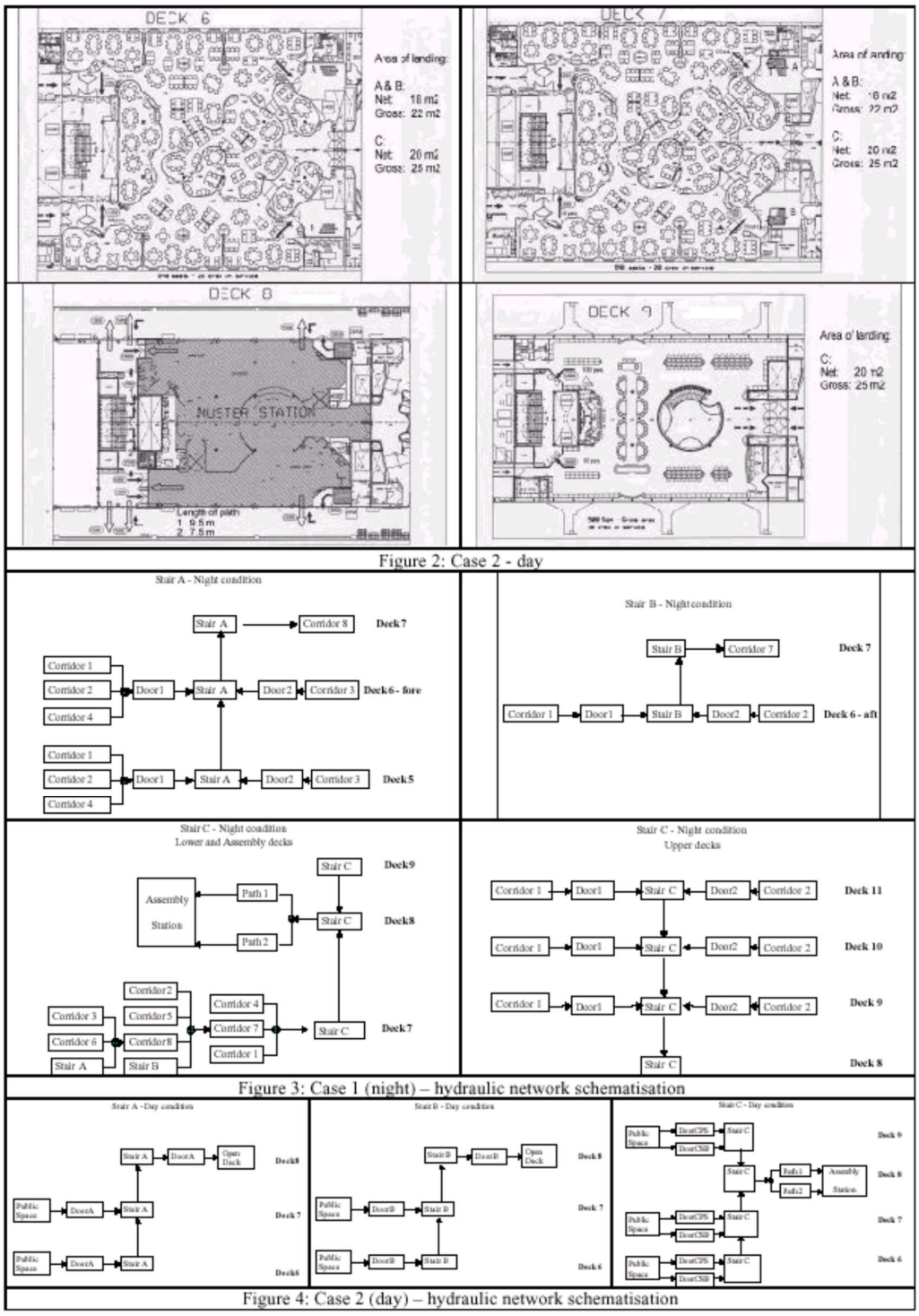


Figure 7.2 MSC.1/Circ. 1533 Case Example Case 2 Day

7.4 Case 2 Results from the IMO MSC.1/Circ. 1533

Using the Guidelines from MSC 1533 (IMO, 2016), in the example, the predicted maximum time of egress (T) equals 437.5 seconds or 7.3 minutes.

The next important result taken from the MSC 1533 Circular is the determination of individual traffic delay points along the selected routes starting from various main vertical zones (MVZs).

This is shown Table 7.1 which presents the results for the calculation of travel duration (T) for each of the travel delay sections forming different decks and stair contributions.

Table 7.1 Delay Points in the Guidelines Example RO-RO Decks

MVZ 1 – Stairs, doors & corridors	**Queues**	**Traffic** (s)	**Delay**
Deck 5 – door 1	Yes	29	
Deck 5 – stair A	Yes	35	
Deck 6 – door 1	Yes	29	
Deck 6 – stair A	Yes	70	
Deck 6 – stair B	Yes	20	
Deck 7 – corridor 7	Yes	40	
Deck 7 – stair C	Yes	107	
Deck 10 – stair C	Yes	67	
Deck 9 – stair C	Yes	103	

The example from MSC.1/Circ. 1533 shows that 55 passengers from Deck 11 have the longest egress duration resulting in a time duration of 426.2 seconds.

7.5 The Model

Taking the topology layout as described in Figure 7.2 for Case 2 (Day), a network model was developed to present the ship layout as shown by the two algorithmic views of the Harel-Koren Layout (Figure 7.3), and the Sugiyama Layout (Figure 7.4). The original layout in MSC.1/Circ. 1533 is difficult to portray as the figures are split into various deck layouts, while the NodeXL layouts are combined for an all-deck representation.

Note that the terminology is based on DxxYYYx where,

D—Deck number xx

YY—Cor (Corridor), Dr (Door) or St (Stair A, B or C).

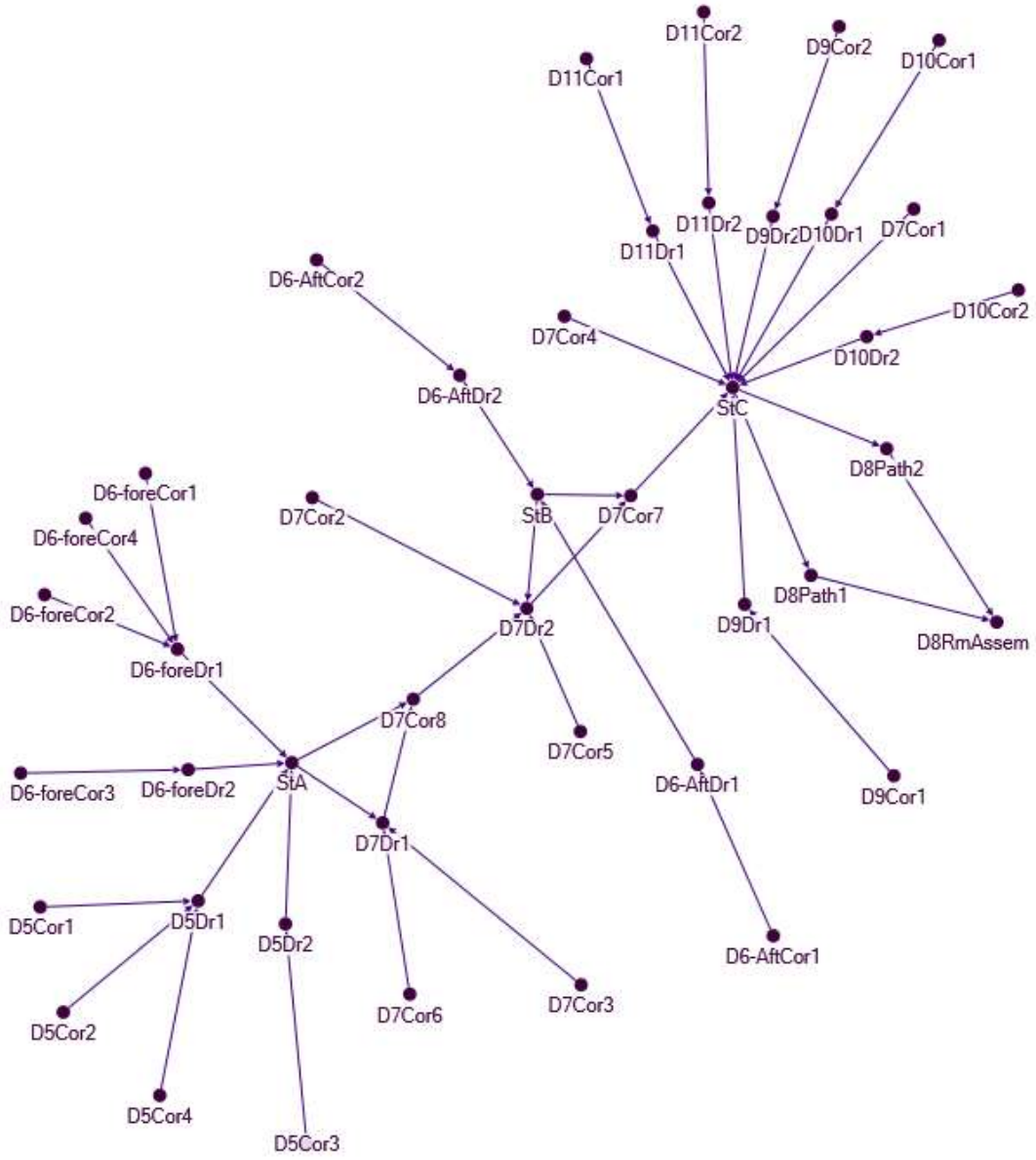


Figure 7.3 RO-RO Harel-Koren Layout (Final Muster Station is Node D8RmAssem).

Figure 7.3 supplies a holistic view, on one page, how the spaces are connected across all decks. It is interesting to note the vertex in-degree (the number of inputs entering a vertex) instances shows potential delayed flow consequences. Stair C is a potential failure point because in order to reach the Muster/Assembly station, designated D8RmAssem, all evacuees need to negotiate this single stair.

The most important outcome of this view is the correctness of the vertex and edge connectiveness which makes for an excellent means to check the model input.

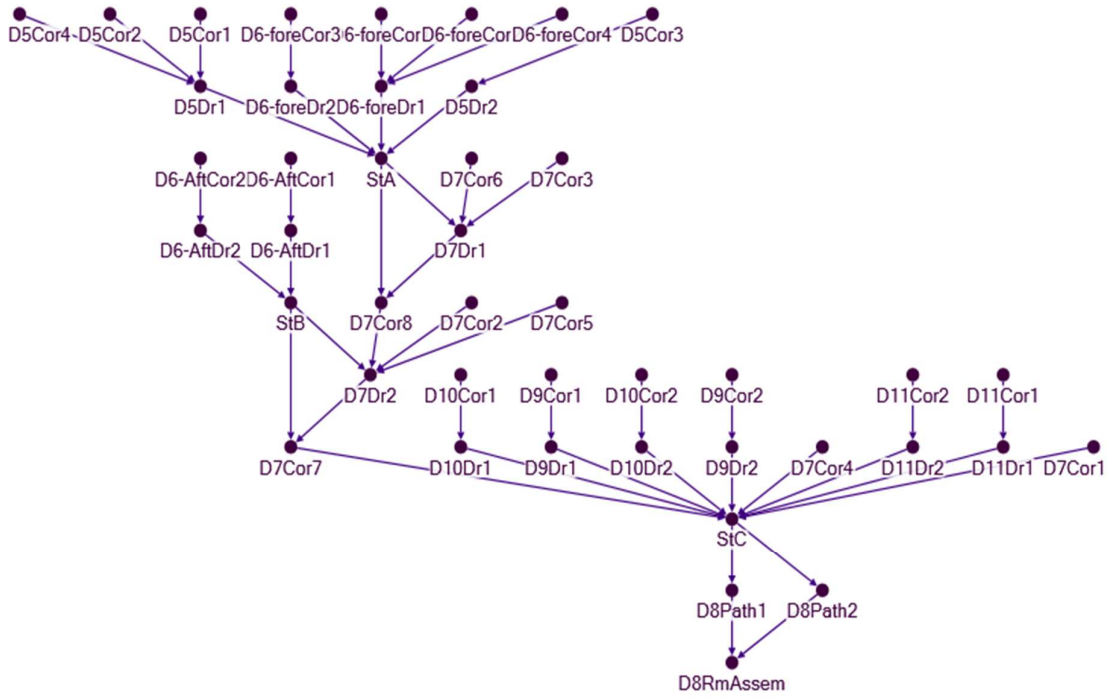


Figure 7.4 RO-RO Layout Sugiyama Layout

Figure 7.4 is quite a different view of the network, showing a quasi-geometrical hierarchy depending on Deck level nomenclature. This layout can be developed by using intelligent vertex labels to make it more deck representative.

Both algorithms produce interesting views to understand the compartment dependencies and the future evacuation route approaches. As modelled, one can discern those routes that if incapacitated will result in not achieving egress to the Assembly area. The main staircase, StC, becomes a bottleneck in the route scheme which raises a significant risk should StC become incapacitated. For design purposes, rethinking the tactical StC staircase layout would be advisable as it shows that this staircase is the only link to the muster station on Deck 8. A solution could be to link D7Cor7 to D8RmAssem. As StC is a multi-deck access route, one could model the separate sections to gain better granularity of the escape options. Deck 7 Door 2 is also in the same category.

At first glance, some simple changes can be made to the stair configurations to increase route flexibility. Major changes that would reduce bottlenecks (see Figure 7.5, in a different layout by introducing a Stair D (StD) to link flow from D7Cor7 directly to the muster assembly point (triangle) on Deck 8 which couples StA directly to the muster assembly area. These two changes increase the out-degree (the number of edges exiting the vertex) for those points. A third change may increase flow by introducing an alternative route in addition will manage the outflow from StC (D8AltRoute). As expected, these changes may or may not be practical, but the information from these algorithms provide evidence that these ships may not be safe in terms of a prompt evacuation at sea.

Figure 7.5 has been labelled Reimagined Layout to the standard layout to be able to distinguish results associated with this alternative layout.

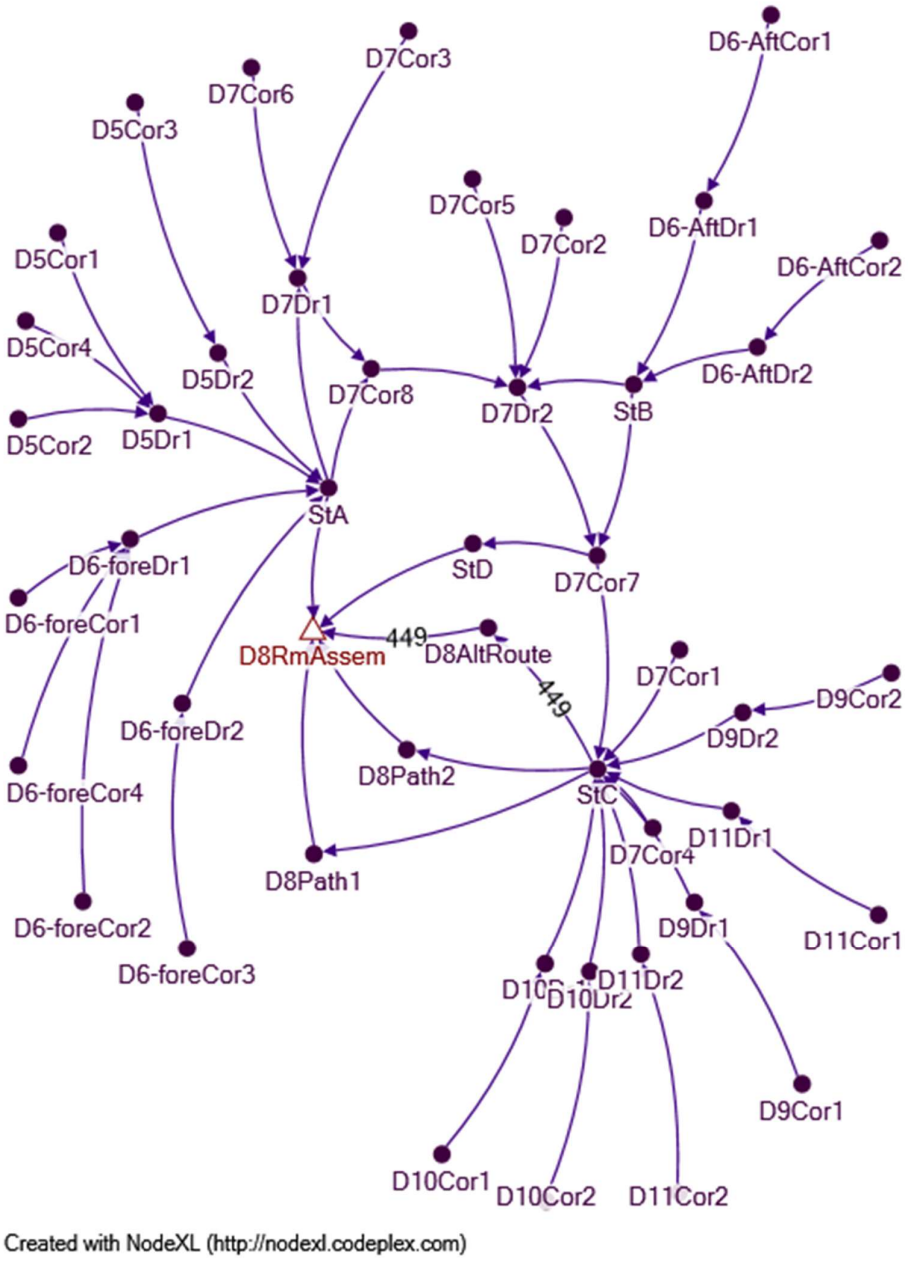


Figure 7.5 Re-imagined Layout (EasyViz)

This layout reconfiguration results in a time difference or improvement in relation to the existing layout and is shown and explained in in Figure 7.11.

7.6 The Network Properties of the Ship Path Topology

Network properties allow the designer to forego complex 3D CAD models or simulations in their layout decision-making process. The approach used for estimating evacuation delay is to use hydraulic analogy, traffic is simulated as ‘abstract flows. The methods

presented herein can be for use by a naval architect to gain insight into the implications of design decisions in the early design stages. This insight results in improved Navy distributed systems design which are easier to design, maintain, and upgrade (Rigterink, Methods for Analyzing Early Stage Naval Disributed Systems Design, Employing Simplex, Multislice, and Multiples Networks, 2014), as well as optimisation of compartment and route layouts with the possibility to re-assess the safety in case changes are made during the operating life of a ship.

While the Network characteristics for the RO-RO topological layout are presented in Table 7.2, the figures relating to these characteristics are shown in Figure 7.6 to Figure 7.9. Note the size and colour of the vertices show its importance in the Network, from brown to dark purple in intensity. The following observations are in order:

1 Network In or Out Degree shows the number of in- or out-bound connections to a specific vertex. In the RO-RO example, StC has clearly the highest number (9) of In-degree connections, while all the staircases show the maximum number of Out-degree connections.
2 Betweenness Centrality measures the extent to which a node plays in bridging spaces in a network or how it fully connects to the network. For the RO-RO Network, StC, D7Dr2, D7Cor7, D7Cor8 and StA are significant in this aspect. Including more vertices in this criterion would ensure that all spaces play a pivotal role in networked connectivity.
3 Closeness Centrality is a measure of the average shortest distance from each node to each other node. The measure can be thought as the number of connections (or hops) to get to all other specific vertices or as distance between vertices. In this case, the lower the score the better. For this example, the node at D7Cor7 has the highest closeness centrality. This shows that this vertex is more central since it is closer to most of the vertices in the graph. This finding strongly corresponds to visual centrality. This node appears in the centre of the graph since it has a high closeness centrality.
4 The Eigenvector Centrality network metric takes into consideration not only how many connections a node has (i.e., its degree), but also the centrality of the vertices it is connected to. For example, the staircase StC has the highest eigenvector centrality (0.136) because its degree is relatively high (9), but also because those vertices it connects to also have relatively high eigenvector centrality scores – for

example, D7Cor7. In contrast, Staircase StA has next highest degree (4) (i.e., number of connections), but those it connects with, do not have high eigenvector centrality scores since they have so few connections. As a result, StA has a lower eigenvector centrality score (0.013). For practical purposes, the knowledge that other spaces or routes have high centrality supplies options for optimising the design layout.

5 The Page Rank criteria supplies a sense of which compartment or route is a core member of the Network because this space is a significant space and connects to other significant spaces. In this case, the staircases StC and StA as well as Deck 7 Door 2 are areas of major interest which can be tailored to ensure traffic is flowing and are not areas of congestion.

Table 7.2 Network Metrics

Node /Vertex	In-Degree	Out-Degree	Betweenness Centrality	Closeness Centrality	Eigenvector	Page Rank
D5Cor1	0	1	0.000	0.004	0.001	0.564
D5Dr1	3	1	246.000	0.005	0.005	1.950
D5Cor2	0	1	0.000	0.004	0.001	0.564
D5Cor4	0	1	0.000	0.004	0.001	0.564
StA	4	2	848.000	0.006	0.013	2.548
D5Cor3	0	1	0.000	0.004	0.001	0.575
D5Dr2	1	1	84.000	0.005	0.004	1.000
D6-foreCor1	0	1	0.000	0.004	0.001	0.564
D6-foreDr1	3	1	246.000	0.005	0.005	1.950
D6-foreCor2	0	1	0.000	0.004	0.001	0.564
D6-foreCor4	0	1	0.000	0.004	0.001	0.564
D6-foreCor3	0	1	0.000	0.004	0.001	0.575
D6-foreDr2	1	1	84.000	0.005	0.004	1.000
D7Cor8	2	1	864.000	0.007	0.018	1.231
D6-AftCor1	0	1	0.000	0.004	0.003	0.574
D6-AftDr1	1	1	84.000	0.005	0.011	0.998
StB	2	2	320.000	0.007	0.034	1.693
D6-AftCor2	0	1	0.000	0.004	0.003	0.574
D6-AftDr2	1	1	84.000	0.005	0.011	0.998
D7Cor7	2	1	900.000	0.008	0.068	1.221
D7Cor3	0	1	0.000	0.005	0.003	0.521
D7Dr1	3	1	166.000	0.006	0.010	1.745
D7Cor6	0	1	0.000	0.005	0.003	0.521
D7Cor2	0	1	0.000	0.006	0.012	0.499
D7Dr2	4	1	982.000	0.008	0.038	2.052
D7Cor5	0	1	0.000	0.006	0.012	0.499
D7Cor1	0	1	0.000	0.006	0.046	0.512
StC	9	2	1139.000	0.007	0.136	4.686
D7Cor4	0	1	0.000	0.006	0.046	0.512
D8Path1	1	1	41.000	0.006	0.054	0.902
D8Path2	1	1	41.000	0.006	0.054	0.902
D8RmAssem	2	0	1.000	0.005	0.026	0.916
D9Cor1	0	1	0.000	0.005	0.012	0.576
D9Dr1	1	1	84.000	0.006	0.050	1.001
D9Cor2	0	1	0.000	0.005	0.012	0.576
D9Dr2	1	1	84.000	0.006	0.050	1.001
D10Cor1	0	1	0.000	0.005	0.012	0.576
D10Dr1	1	1	84.000	0.006	0.050	1.001
D10Cor2	0	1	0.000	0.005	0.012	0.576
D10Dr2	1	1	84.000	0.006	0.050	1.001
D11Cor1	0	1	0.000	0.005	0.012	0.576
D11Dr1	1	1	84.000	0.006	0.050	1.001
D11Cor2	0	1	0.000	0.005	0.012	0.576
D11Dr2	1	1	84.000	0.006	0.050	1.001

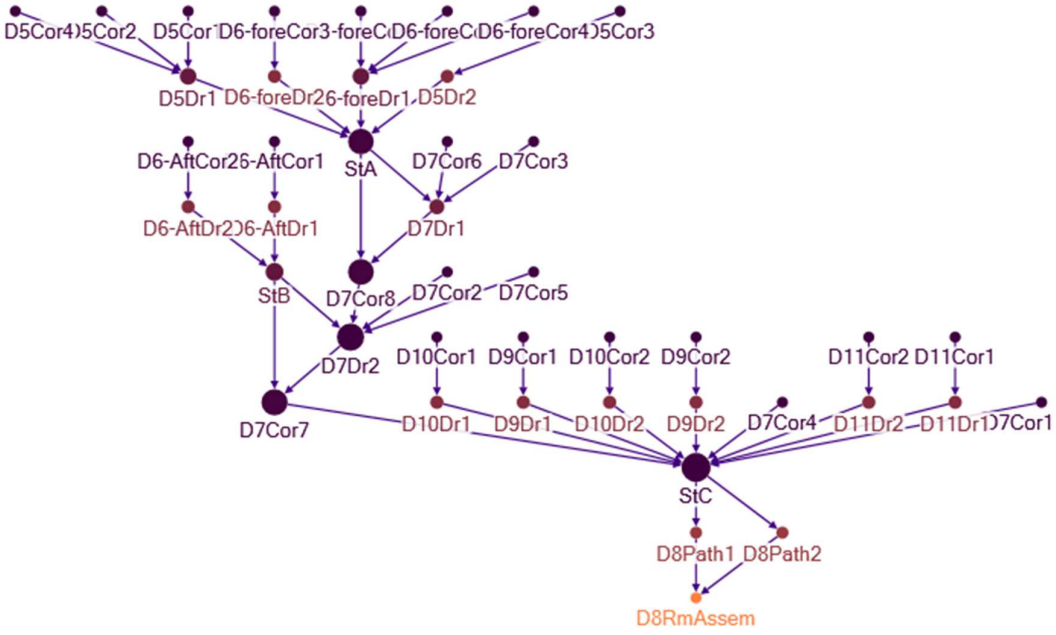


Figure 7.6 Betweenness Centrality Plot

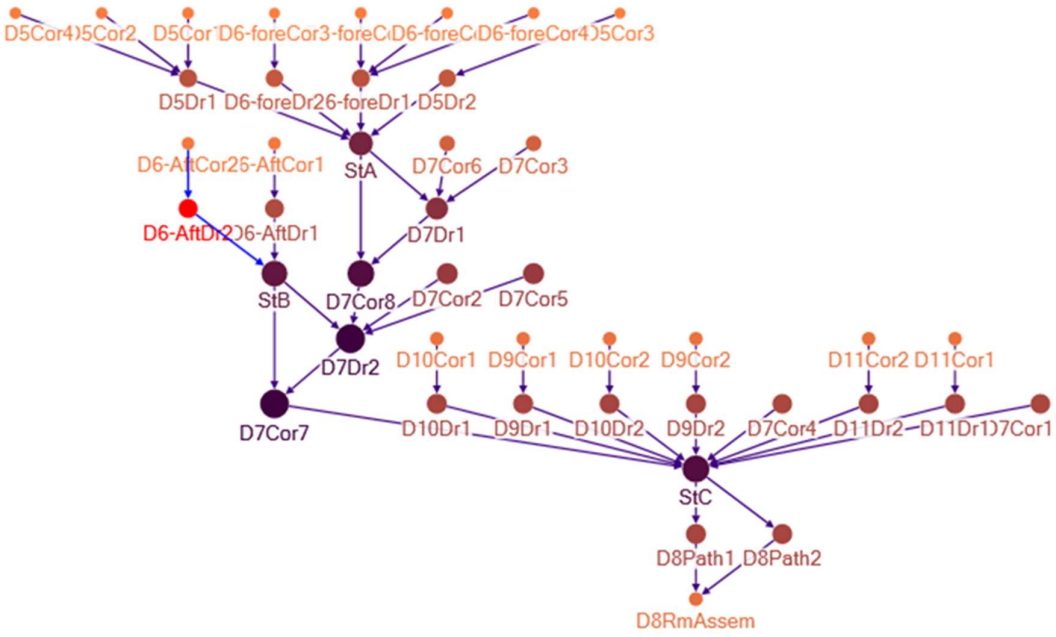


Figure 7.7 Closeness Centrality Plot

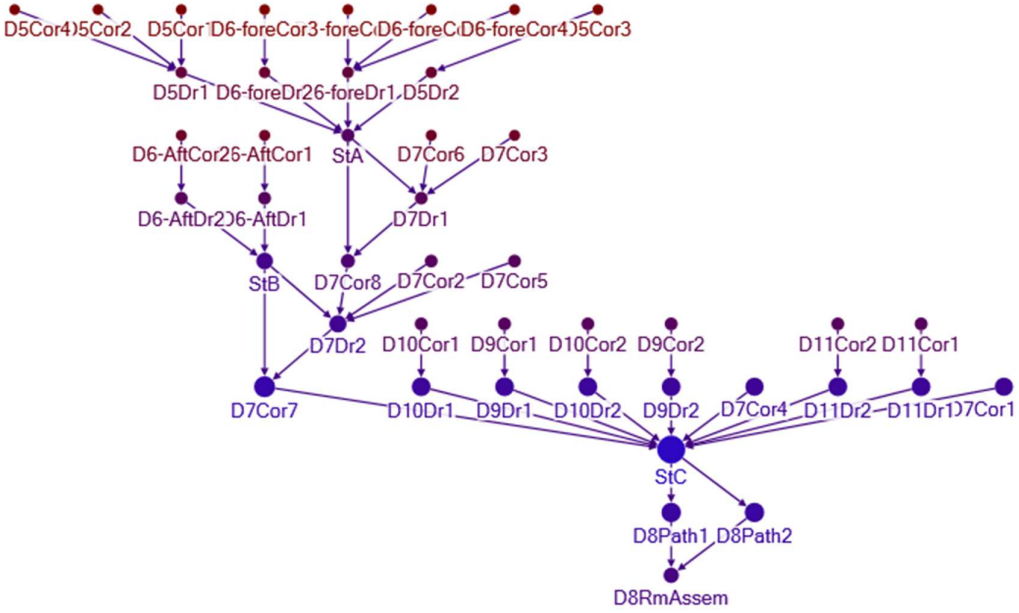


Figure 7.8 Eigenvalue Centrality Plot

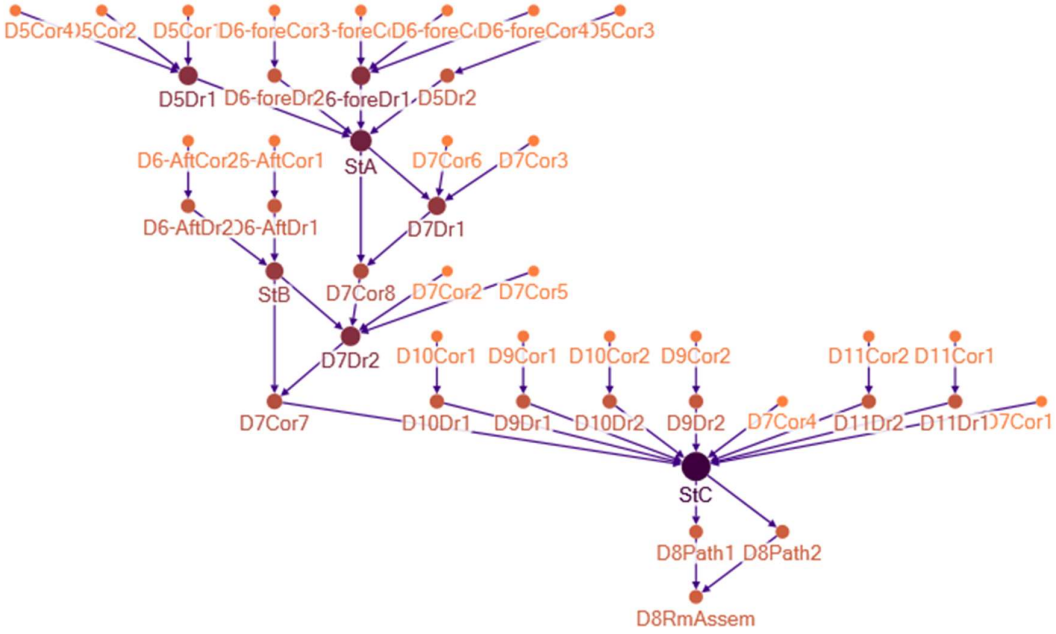


Figure 7.9 Page Rank Plot

The results clearly show the importance of the deck-to-deck component layout of the evacuation route. As this is a simple case, the added network property results are not unexpected. However, if applied to a ship with many decks and compartments, these

properties are not easily discerned at a detail level and require a network analysis procedure to understand the complexity of the ship space connectivity. This is of significant value to ship layout design.

The goal at this stage of early design is to create a new, novel set of concepts, measures, and methods that will allow a single ship and naval architect, or small team of naval architects, to understand the impact of distributed compartment and route system design decisions in the early phases of the design process, all the while, exploring configuring and reconfiguring layouts fast discovering the final form of the ship without the need for 3D system models. Indeed, a 3D layout would not allow the visualisation aspects of the measures outlined above.

Most importantly, the analysis shows potential areas of delay – Stairs A, B and C as well as Deck 7, Corridors 7 and 8. This finding corresponds to the results specified in the scenario example from MSC.1/Circ. 1533 to a certain degree noting that the Stairs geometry is slightly different.

This simplified form of a novel application of network analysis rethinks and re-investigates the nature of ship layouts.

7.7 Case 2 (Day) Route Optimisation: Shortest Time to Evacuate

The earlier section explored the network characteristics of the model that have been developed with geometry impacts defined and considered to propose refinements to the layout. Prediction is discussed next.

7.7.1 Factors that Impact Evacuation Movement

Calculation of egress is sensitive to overall path characteristics such as geometry (path obstacle(s), widths, distance), human behaviour (exit choices and familiarity) and environmental conditions (ship sway, fire, smoke or flooding, and traffic). Generally, some items are occupant characteristics, whereas others are ship characteristics. The analysis presented examines ship characteristics which can be quantified and modelled.

One of the most significant aspects of evacuation is traffic which causes delays and increased risk. For design purposes, the model is best used to find routes that may have potential delays due to traffic. The capacity rating of the path can be adjusted to change

traffic flow. Capacity can be varied as a change and is found in the path. This valuable information is useful to have in a ship's design phase.

The approach used for estimating evacuation delay is the hydraulic analogy which finds traffic simulated as 'abstract flows. Another approach considers the behavioural aspects of the people, however, for this example, the means to consider behaviour will be discussed later in at Section §Chapter 8. Prerequisites for either of these approaches are based on the availability of information or data on the people movement, such as speed, rate of travel along a corridor, ramp and/or stairs. The speed on stairs depends on stair geometry, as well as the passengers' capabilities and capacities (see Chapter 3).

7.7.2 Application of Evacuation Modelling to the RO-RO Ship

MSC.1/Circ. 1533 supplies assessment scenarios for this analysis. For this assessment, the primary Case 2 (Day) evacuation scenario is used and is supported by:

- Effecting improvements to evacuation performance which are linked to congestion points and/or critical areas with the view to minimise these and to supply recommendations
- The performance standard for the Case 2 (Day) is assumed to be 60 minutes, as for RO-RO passenger ships

1 The example RO-RO ship is based on an existing operational ship layout and includes 10 decks with connecting corridors and stairs. Five decks have been considered in the model.

2 The corridors connect to doors, stairs, or openings. The goal is to reach the Assembly Station on Deck 8.

3 Each corridor or door has properties relating to length and width in metres (Note that a door has no length, only width).

4 Corridors specify the number of crew or passengers that occupy the corridor space at a specific time as a distribution, including 449 evacuees in total.

The performance standard from MSC 1533 is used. It defines the important parameters and puts into perspective the expected conditions and evacuation response results.

7.7.3 Compartment Dimensions

Table 7.3 Vertex Geometries

Node/Vertex	In-Degree	Out-Degree	Wc (clear width) (m)	Length (m)	Area (m^2)	Occupying Persons
D5Cor1	0	1	0.9	13	11.7	11
D5Cor2	0	1	0.9	20	18	12
D5Cor3	0	1	0.9	9.5	8.55	8
D5Cor4	0	1	0.9	20	18	11
D5Dr1	3	1	0.9	0.1	0.09	0
D5Dr2	1	1	0.9	0.1	0.09	0
StA	4	2	1.35	9.34	12.609	0
D6-AftCor1	0	1	0.9	13	11.7	11
D6-AftCor2	0	1	0.9	20	18	12
D6-AftDr1	1	1	0.9	0.1	0.09	0
D6-AftDr2	1	1	0.9	0.1	0.09	0
StB	2	2	1.35	4.67	6.3045	0
D6-foreCor1	0	1	0.9	13	11.7	11
D6-foreCor2	0	1	0.9	20	18	12
D6-foreCor3	0	1	0.9	9.5	8.55	8
D6-foreCor4	0	1	0.9	20	18	11
D6-foreDr1	3	1	0.9	0.1	0.09	0
D6-foreDr2	1	1	0.9	0.1	0.09	0
D7Cor1	0	1	0.9	6	5.4	4
D7Cor2	0	1	0.9	9	8.1	4
D7Cor3	0	1	0.9	15	13.5	6
D7Cor4	0	1	0.9	6	5.4	4
D7Cor5	0	1	0.9	14	12.6	6
D7Cor6	0	1	0.9	15	13.5	2
D7Cor7	2	1	2.4	11	26.4	0
D7Cor8	2	1	2.4	9	21.6	0
D7Dr1	3	1	0.9	0.1	0.09	0
D7Dr2	4	1	0.9	0.1	0.09	0
StC	9	2	1.4	18.68	26.152	0
D8Path1	1	1	2	9.5	19	0
D8Path2	1	1	2.5	7.5	18.75	0
D8RmAssem	2	0	4	10	40	-449
D9Cor1	0	1	0.9	36	32.4	55
D9Cor2	0	1	0.9	36	32.4	55
D9Dr1	1	1	0.9	0.1	0.09	0
D9Dr2	1	1	0.9	0.1	0.09	0
D10Cor1	0	1	0.9	36	32.4	48
D10Cor2	0	1	0.9	36	32.4	48
D10Dr1	1	1	0.9	0.1	0.09	0
D10Dr2	1	1	0.9	0.1	0.09	0
D11Cor1	0	1	0.9	36	32.4	55
D11Cor2	0	1	0.9	36	32.4	55
D11Dr1	1	1	0.9	0.1	0.09	0
D11Dr2	1	1	0.9	0.1	0.09	0

The dimensions have been extracted from MSC 5133 (shown in Table 7.3).

As noted above, and for context here, the label refers to the location onboard ship, i.e., in the form 'DeckNum, Space ID', where DeckNum is the deck number and Space ID is the node identifier.

7.7.4 Ship Modelling Aspects and Assumptions

Aspects in the development of evacuation prediction relate to capability, capacity and movement velocity. These parameters have been introduced to aid the prediction modelling. The optimisation of the route includes the following aspects and simplifying assumptions:

1 Passenger travel velocity is based on building data and adapted to fit within the context of this analysis
2 Passenger age, sex and skill levels have been averaged out for simplicity's sake because the aim of this research was not to better define travel metrics and parameters
3 Group behaviour is not considered, albeit congestion is included. This aspect changes global movement time.
4 Damage, smoke, heat and toxic conditions and ship sway effects have not been included in this model
5 Ship motion and trim have not been considered in this case example. It is acknowledged that this aspect changes movement time. Technical data has not been cited to develop this development.

Density capacity limitation is defined as the density of evacuees traversing a vertex and is calculated and defined using people density. This capacity is used to define the congestion points when the density is equal to or greater than 3.5 persons/m^2.

Evacuee movement speed is by Table 3.4 of the MSC.1/Circ. 1533 It is assumed that for all ages and sex, there is a mean value and a standard deviation, and therefore movement velocity can be modelled as a stochastic parameter in the prediction. The final velocity for each evacuee egress is calculated using the inverse of the normal cumulative distribution for a specified mean and standard deviation using random probability as an input to the Monte Carlo analysis. This leads to a research assumption that Monte Carlo analysis is a proper technique to assess movement across the first three aspects listed about in this section.

To decide the vertex flow characteristics, one optimises (maximum or minimum) the final egress duration value subject to 'network flow' constraints using the MS Excel Solver® Macro. The final egress duration value is subject to network flow constraints and calculates the number of people traversing specific vertices to minimise evacuation duration. The Excel Spreadsheet Excel Solver® is used for its accuracy and consistency in these calculations. Note that the non-linear Generalized Reduced Gradient (GRC) solver was used due to the random input quantities (Frontline Solvers, n.d.).

The IMO evacuation example is presented in Appendix 2 of MSC.1/Circ. 1533. Listing both a simplified and advanced analysis method. Using these techniques, personnel traversing vertices had no options to use alternative paths. Furthermore, the MSC.1/Circ. 1533 Guidelines do not allow for alternatives to be assessed and the prime focus is on crowding and delays and assumes all identified paths are available. The analysis in MSC.1/Circ. 1533 is conducted by a hand analysis, with no path optimisation conducted.

The prediction model for the Case 2 (Day) scenario was developed using influencing factors that governed the final process method as listed in detail in Section § 7.2. To summarise:

1 the mathematical approach develops realistic ship evacuation simulation
2 the methodologies are based on building evacuation studies
3 the example is based on a benchmark scenario for daytime, not an actual evacuation
4 The routes are found where evacuation duration is calculated for each path to the Muster station at Assembly Area on Deck 8
5 The path with the longest evacuation duration is evacuation duration.

To express uncertainty in the final crew movement solution, a Monte Carlo analysis is conducted to find the most likely evacuation time duration (> 600 iterations). Note that earlier stochastic modelling has been investigated in the design of the Landing Ship Dock (LHD) platform where behaviour modelling, uncertainty and deterministic modelling produced compliant evacuation times in accordance with the MSC 1238, the precursor to MSC 1533 (Bellas, et al., 2020).

7.7.5 Case Study Prediction Results

To show the flexibility of the prediction tool, the evacuation prediction solution is developed for four constraint cases but is not limited in the number of constraints that can be implemented. The four constraints are

Constraint 1 – Unconstrained model which meets a nodal conservation flow balance check (see Figure 7.10)

Constraint 2 – Maximum number of persons per link, e.g., except for Deck 8 (see Figure 7.12.

Constraint 3 – Route closure, however, it cannot be that the solution cannot be found because of flow balance. Route options are needed if one route is closed. This condition reflects any circumstance that involves fire, gas, or lighting constraints (see Figure 7.13.

Constraint 4 – Closure of the two arteries to the Assembly Area on Deck 8. The new route is longer and narrower (reduces from 2.5 m to 0.6 m) and provides an insight into how geometry affects egress time (see Figure 7.14).

The stairs A, B and C are hazardous components should they fail and present the passengers no way to reach the Assembly Area. This circumstance can be simulated in the design phase. For example, if Staircase C connections to the Assembly areas is incapacitated, the route could be optimised for this condition by changing the node link D7Cor7 to StA to be an undirected link while connecting D7Cor7 directly to the D8 Assembly area. This route optimisation gives the persons using StC another choice for escape. The results show vertices, their corresponding edges (links) and the number of persons crossing the edge.

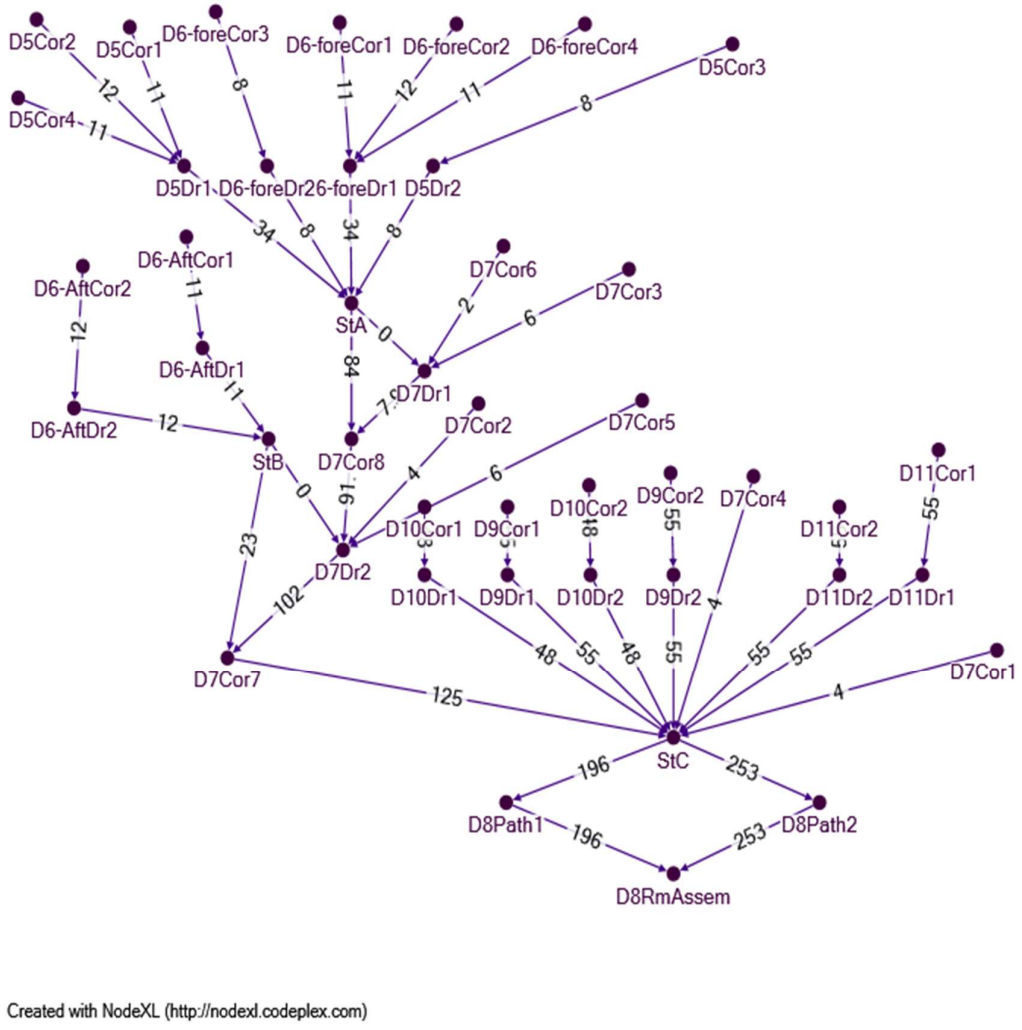


Figure 7.10 Transfer of Evacuees under Constraint 1 with Max. Egress Time 571.7 seconds.

Figure 7.10 presents the layout for Constraint 1 and is the validation constraint. Each edge describes the number of passengers traversing the edge between vertices. The model shows the final passenger count arriving at D8RmAssem totals the number of passengers on ship. The predicted egress time value is 571.7 seconds or 9 minutes 31.7 seconds and is higher than the MSC.1/Circ. 1533 result of 436.2 seconds or 7 minutes 16.2 seconds. The difference can be attributed to the insufficient clarity of the RO-RO data and details and the modelling preference of detailing the many sub stairs in the Figure 7.2 to one stair only, StC. Traffic delay is expected to be higher than the MSC 1533 result given the density of traffic; optimisation has different numbers of passengers on different paths. The simulation sums the maximum time for each deck to be more representative of the

real case, assuming all evacuees start at the same point in time. A more granular solution may see beneficial outcomes appearing.

The results are encouraging. Nevertheless, further work is needed to define better time predictions for the last passenger to affect a better outcome.

As discussed earlier in Section § 7.6, the network layout was recalculated by eye with reimagined layout by adding alternative routes emanating from the stair StC to the Assembly area. The same number pf passengers (449) arrive at the Assembly Station. The result also shows the passenger redistribution for the other paths leading to the Assembly Station. An improvement in evacuation time was achieved to a time of 490 seconds (see Figure 7.11 an improvement of 92 seconds.

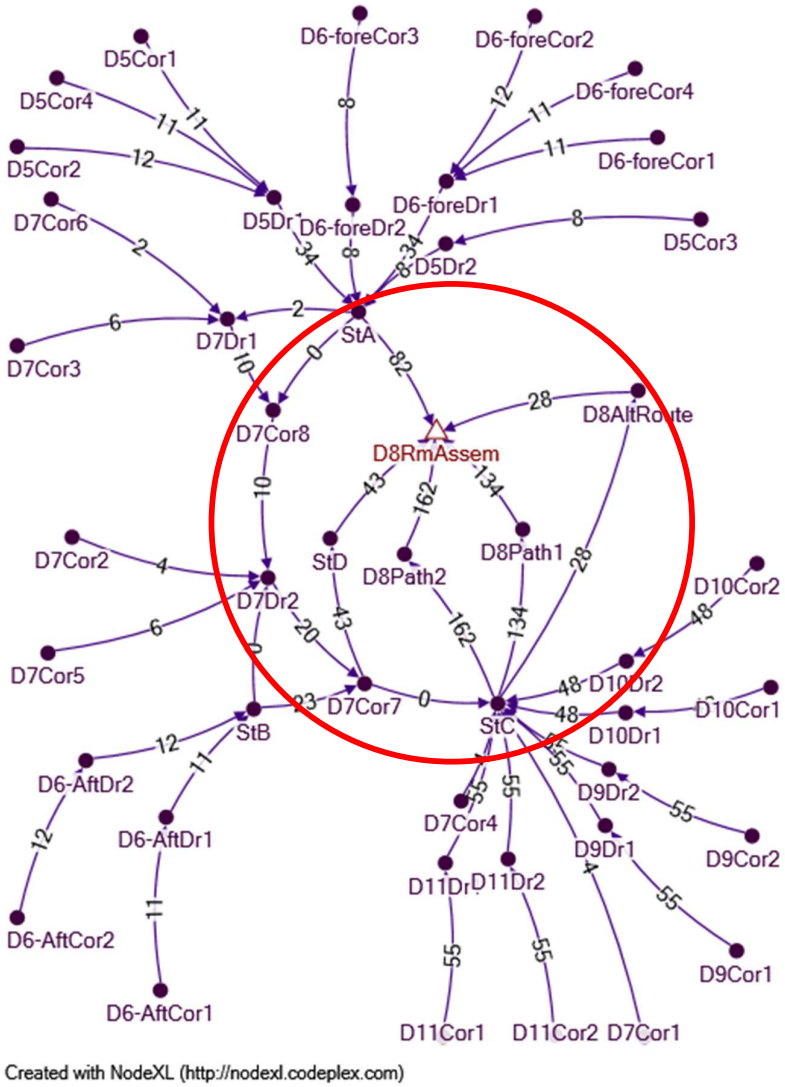


Figure 7.11 Re-imagined Quick Change

A first reconfiguration of the main Stair C and increasing the number of paths to the Assembly area resulting in a reimagined layout resulted in a reduced evacuation prediction value of 480 seconds, which is a 19% improvement over the standard Constraint 1 layout value of 571 seconds.

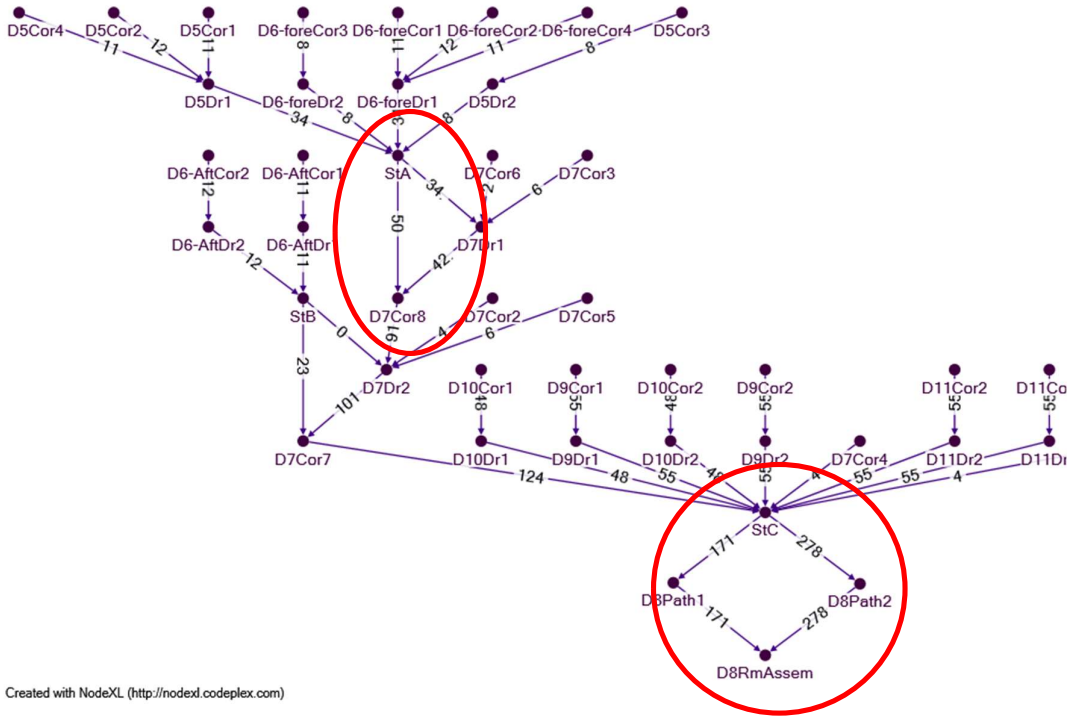


Figure 7.12 Solution Constraint 2 with Predicted Egress Time 629.8 seconds

This plot shows the change in result when constraints are placed on paths and/or limiting the number of people traversing vertices. These changes are limiting the Edge StC to D8Path1 to 175 persons and limiting to 50 people the Edge StA to D7Cor8.

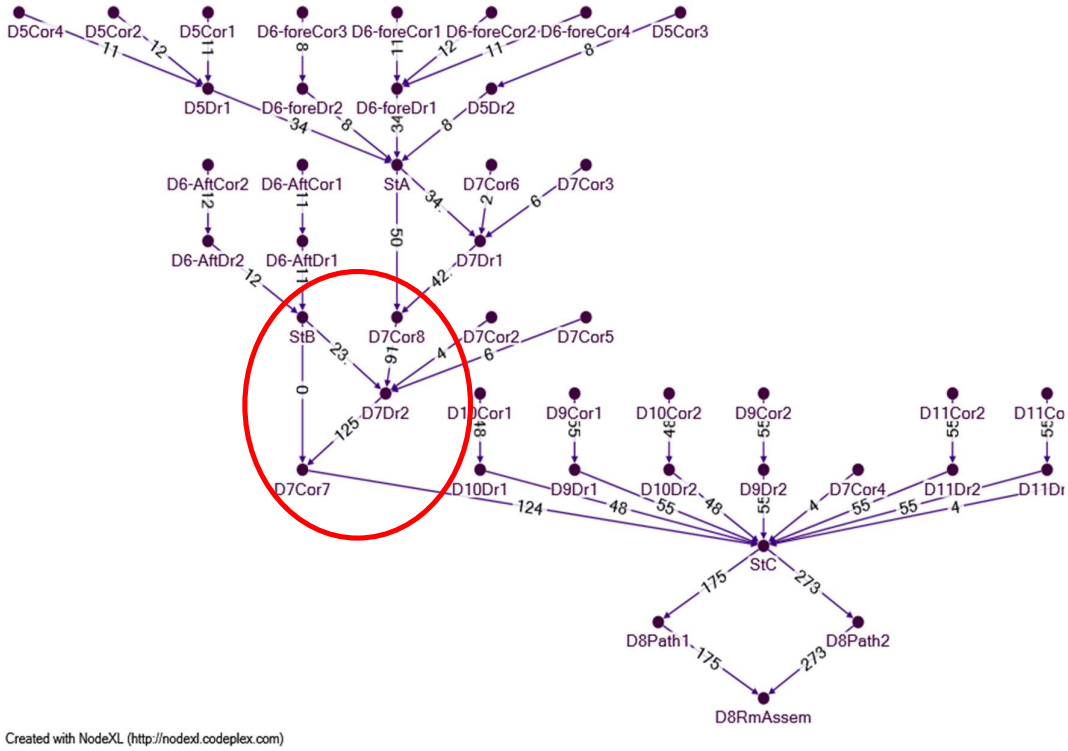


Figure 7.13 Solution Constraint 3 with Closure of a Major Route with Predicted Egress Time 669.2 seconds

When a major thoroughfare is closed such as that showed in Edge StB to D7Cor7, evacuation time increases, as expected.

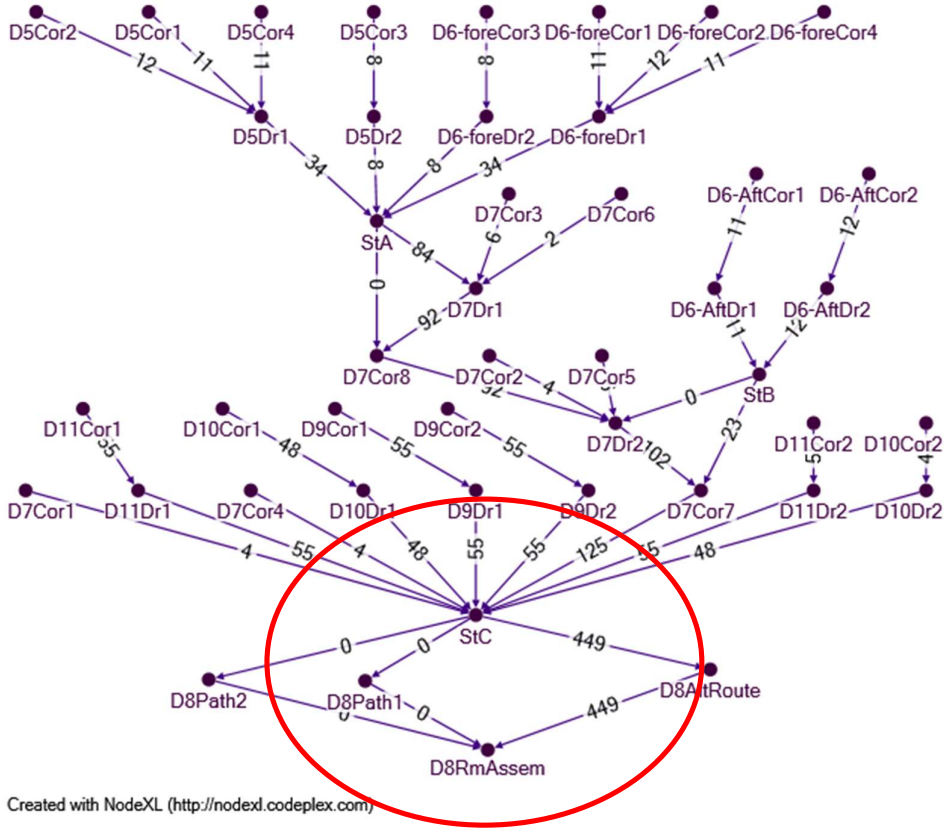


Figure 7.14 Solution Constraint 4 with Predicted Egress Time of 1170 seconds

The plot shows the influence of the blockage of two of the three access edges to the final muster station D8RmAssem. Prediction time calculates major delays occurring on this sole edge StC to D8AltRoute.

7.7.6 Concluding Remarks - Results

Figure 7.10 to 7.14 proves the power and versatility to divert personnel routing in the cases of found constraints. The algorithm will try to find the optimised route and minimise time. In Figure 7.14, the egress time increases dramatically given the clear width of D8AltRoute is reduced to 0.6 m wide as against the original route widths of 2.5 m for D8Path 1/2.

Also, the quick re-imagining of configuration by introducing alternative paths on the fly, (see Figure 7.11), enabled the predicted egress time to decrease by 19%.

Several aspects are noteworthy:

1 All vertices need alternative exit routes so that the algorithm can optimise the egress dynamics, i.e., out degree should be > 1, if possible. The greater than 1 out degree should be considered for design of the ship layout as a means to use a safer alternate escape path.

2 Smoke, gas, lighting, and obstructions can be modelled to decide the effect on passenger velocity as discussed in the SFPE Handbook (SFPE Task Group , 2019). This can be undertaken by changing movement velocity along that specific path.

3 It is easy to add a space or vertices to connect to the network, reducing centrality and eigenvector attributes

4 If the node relationship is bi-directional, then a loop potentially can be created where the solution cannot converge to an optimised solution. Initial node links and final destination vertex links require directional characteristics; the network model needs to be directional with a source and sink.

7.8 Additional Findings - KPIs Design Support

The figure of merit (FOM) is calculated as:

FOM = (1.25 (R+T) + 2/3 (E+L))/n

FOM <= 1.0.

For daytime scenarios, R = 5 minutes

E+L = 30 minutes

T = RSET = 1170s, see Figure 7.14

n = ASET = 80 minutes

FOM = 0.64

This calculation shows a positive outcome for the shole of evacuation simulation. Constraint 4 supplies the work case scenarios when several of the paths are closed due to mitigating environmental conditions, and therefore results in a higher evacuation time of 1170 seconds, but still is within the ASET requirement. The FOM supplies a quick evaluation of the chosen design decision. The designer is able to set the goal and design decisions can be evaluated against this criterion.

7.9 Delay Time

This KPI is applied to all vertices to find the potential delay in the network when the specific flow reaches a maximum at a specific point.

Td = P / (1.3*We)

For the Constraint 1 result (see Figure 7.10), D8Path 2 has 253 evacuees traversing the vertex, with an effective width of 2.5 m. The Td KPI = 77.8 seconds which is the flow delay time associated with the exceeding specific flow constraint at 1.3 persons/second/metre (width), when traversing the vertex. A larger effective width reduces the delay time.

7.10 Concluding Remarks

This Chapter described a case study, presenting an integrated view of the entire process of the evacuation prediction method. The case study is specifically tailored by using scientific and industrial standard practice to meet the aims of this research. There are sufficient details to understand the processes and methods employed.

It is interesting that like complex problems, the evacuation method has been broken down into several stages exhibiting stand alone methods on their own, and have come together to form an understandable way to approach evacuation prediction.

Chapter 8 Monte Carlo Analysis to Consider Uncertainty in Velocity

8.1 Introduction

For the next step of creating the solution, the Monte Carlo technique was used to introduce a random variable parameter to formulating movement speed under stochastic considerations. The approach used the velocity data presented in Figure 5.13 and determined the mean value and standard deviation of the low and high averages. An Excel formula is used that returns the inverse of the normal cumulative distribution for the specified mean and standard deviation with the probability set as random (Excel Functions, 2020). The Monte Carlo is run 600 times with each iteration displaying a random probability.

The results are filtered depending on the constraint. Very low and very high values are discarded so the results are not skewed to extreme values as the random probability ranges and varies from 0 to 1. The results are presented for the sole configuration known as Constraint 1. Only one constraint solution is supplied to present the approach considered for Monte Carlo analysis.

Table 8.1 Monte Carlo Analysis Initial Results for Constraint 1

Variable Velocity	**Velocity Mean** (m/s)	**Standard Deviation** (m/s)	**Final Mean Time for Egress** (s)	**Final Standard Deviation** (s)
Low Velocity Averaging	.472	0.185	**1076**	322
High Velocity Averaging	0.671	.274	**898**	286

Table 8.1 presents the results of the Monte Carlo Analysis for the Constraint 1 case, where the original calculated deterministic result was calculated as 571 seconds. To conduct this Monte Carlo analysis, the movement data presented in Figure 5.13 was examined to extract the differences between high and low movement velocity data. When modelled as a stochastic input parameter for the Monte Carlo analysis, values for the mean and

standard deviation of velocity are calculated. The mean predicted time was calculated over 600 iterations using a random probability, each iteration providing on value. These mean values for movement velocity are quite different from the original calculation. The egress times have their own standard deviation around the mean value (taken from the 600 iterations). For example, using the low averaging movement velocity data results in a mean prediction range of time 1076 s, whilst using high movement velocity data results in a mean time of 898s. The mean calculation considers all the 600 random iterations; data outliers play a significant impact. At this point, the usefulness of the Monte Carlo technique can be clearer as there is a reasonable standard deviation around the mean time result and so, a finer assessment is needed to understand the range of Monte Carlo results.

To show this, another step is used on the data so as to include vital sources of losses in the lack of data quality relating to the effect of situation awareness. A technique known as a Pareto Analysis (Nankana, 2005) is used. A Pareto analysis is starts with the hypothesis that for the evacuation analysis, the total effects of randomising an outcome can be relied on 80% of the outcomes being found.

Figure 8.1 shows that 80% of outcomes straddle 810 seconds to 940 seconds in the worst case, and therefore, the Monte Carlo view is a better means to understand the analysis. Better granularity aids the prediction by using a bounding Pareto solution to supply an improved approach to decide evacuation time.

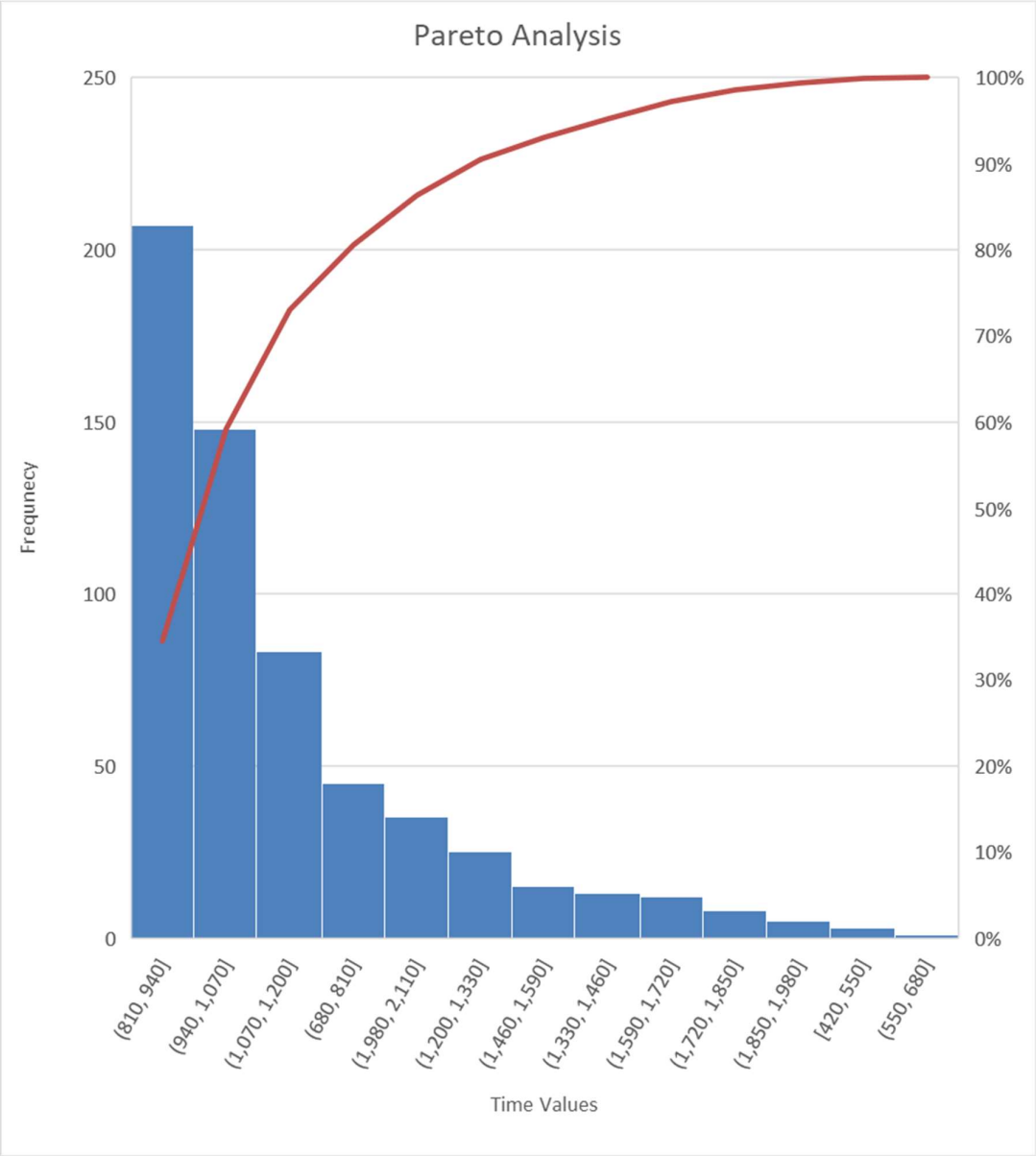


Figure 8.1 Monte Carlo Pareto Analysis (Low Average Example)

8.2 Discussion of Simulation Results

The model analysis depicting a predicative algorithm as presented in MSC.1/Circ. 1533 and an algorithm using Monte Carlo analysis to consider uncertainty for Constraint 1 is presented in Table 7.5. The Monte Carlo result covers uncertainties related to age, capability, fitness, situation awareness and capable knowledge. For design system safety purposes, the higher value of 940 seconds is chosen for design purposes.

Table 8.2 Graph Theory in Comparison to MSC.1/Circ. 1533

MSC 1533 Results (s)	**Predictive Result using Graph Theory** (s)	**Monte Carlo Result Range** (s)
438	571	810 → 940

The following conclusions can be made:

1 The versatility of this approach opens predictions to be made quickly and efficiently and plentiful data can be reassessed, reworked, and reconsidered to approach an ideal solution to design and assessment.

2 The result most useful for comparison is the predictive result of shown in Table 8.2. The network approach over predicts the MSC 1533 by 133 seconds. This could be due to several conditions, namely: both models use slightly different velocity data; The network approach aggregates the stairs nodal representation as one node; and, the MSC 1533 model is optimised by hand, while the network analysis optimisation is computer derived.

3 The simulation framework introduces positive design aims to pursue and to characterise as So Far as Reasonably Practical (SFARP) safety outcomes

4 Evacuation prediction can be represented by a network graph and can be described by eigenvalue analysis, which opens the field to comparing networks by common descriptors, such as complexity. The modelling technique using Graph Theory is proper for the task presented and can produce consistent and credible results

5 A network world view representation of the ship's paths provides clarity and useful observation of topographical details with evacuation topology presented as a 2D map. The direction and the number of evacuees traversing vertices is clearly annotated

6 The network model shows the ability to see clearly localised deficiencies in the movement capability

7 The development of egress time increases due to added constraints, as shown in an example related to Constraint 1

8 Monte Carlo is a useful tool to find the effect of uncertainty on the velocity outcomes. Movement velocity was the only variable subject to stochastic modelling, but it shows the viability of using this technique to include other variables in the simulation. The

Monte Carlo simulation can be used to find the safety factor to be applied to the total evacuation time

9 The requirement to model sources and sinks is to be carefully explored with the network ideally modelled as directed graphs. Any loop back links produce infinite loop characteristics if placed in paths that cannot execute a solution

10 The network model is flexible and allows for changing the vertex and edge topography.

This case study shows the value of using network analysis coupled to Monte Carlo analysis for prediction purposes. The prediction overcomes the limitations of complexity and produces efficiencies in the calculation methods. The deterministic solutions from MSC.1/Circ. 1533 and the research prediction are close, the closeness explained by known and unknown data variances. Monte Carlo analysis is a positive method to mitigate uncertainty and can be exploited to supply a consistent application of evacuation.

8.3 Model Verification, Validation and Associations

The simulation is based on network analysis theory and linear programming. It uses a well-established Excel Solver® engine that has proven efficient and correct in the calculation and optimisation of linear simultaneous equations. Calculations are based on a set of consistent set of linear equations that meet the constraint requirements to conduct optimisation. An error occurs if this requirement is not met. For these set of calculations, it passed the vertex flow balance checks. This approach results in prediction calculations to be correct, consistent, and repeatable and supports the verification context.

The simulation modelled evacuation performance as outlined in the MSC.1/Circ. 1533 Guidelines. The Guidelines showed RO-RO ship results also confirmed showed this be consistent, correct, and repeatable (Capizzi & Marian, 2019, 2021). These results are promising and supply ample guidance to set up a first step to extend the simulation to the extent this research case covers. For the case study, the same correlation applies as discussed in section § 7.7.5, the results are within 30% and is considered adequate for verification purposes and is acceptable for validation of the prediction approach. The differences have been explained relating to the difference justification; insufficient data validation, clarity of ship example and a conscious decision to visually optimise the stair

configuration leading to added delays on StC. These differences reflect the insufficient clarity by the analysis carried out in the MSC.1/Circ. 1533 example.

Shortest path algorithms were tried and tested with many simpler stock and flow models and found to supply correct solutions (MIT, 2013). The approach using Excel Solver® calculates the solution with two major checking tools, i.e., the flow balance criterion and the boundary constraints. Both Excel Solver® criteria were met for the simulation constraint cases included in the case study simulations.

The network was modelled to enable simple and correct display of connectivity and their properties, as shown in Table 7.2. Visualisation is the crux of the NodeXL network optimisation algorithm. The centrality network metrics take into consideration of not only how many connections a vertex has (i.e., its degree), but also the centrality of the vertices that are connected (i.e., its connections and importance place in the connection hierarchy). In this case, Figure 7.10 through to Figure 7.14 show the most influential vertices in the network and are as expected for this simple case study. For design purposes, these layout tools/metrics should be considered for the design application. This capability can be used to pin-point critical areas of node access, checking redundant safety paths and the adequacy thereof. The same algorithm supplies 'Google' ranking of all the vertices. This means of objective topographical viewing involving vertex metrics is the first step in parametrising design issues, as well as mitigating existing instances to movement safety concerns at the outset of preliminary design. This technique of applying network metrics is an important discriminator for validation purposes.

A performance framework was introduced, taken from MSC.1/Circ. 1533. Added to this framework were KPIs that were developed to tackle the most significant sources of egress time, the delays due to traffic flow along a pathway. This KPI can be used for designers to develop a detailed evacuation route design that minimises delay and can also be used to direct traffic along paths that wouldn't normally be used to minimise the delays. The work performed inherently supports the validation process.

To include some degree of uncertainty, the simulation included passenger movement velocity as a function of path topology, passenger age and disability issues by assuming that the risk approach covered by Monte Carlo was a good mitigator of evacuation risk. Monte Carlo aided the mitigation due to the uncertainties related to behaviour and capability. Thereby, the network was stochastically modelled to decide the variances seen

in the tabled movement velocity data from the building industry. This stochastic data was subsequently used in a Monte Carlo solution using a random probability of occurrence for movement (velocity), thereby supplying a best estimate based on the number of outcomes and realistic scenarios. The spread of the results also confirmed the final result solution.

The simulation analysis was also consistent determining traffic delay points in the network with MSC.1/Circ. 1533.

8.4 Concluding Remarks

The simulation of the case study from MSC 1533 supplies an efficient and resource-optimised solution to evacuation prediction. Evacuation paths can be modelled that use cost functions for time which can account for difficulty of cross compartment movement, difficulty of compartment-to-compartment movement, constraints (if included, for example of smoke and/or fire, water, dark corridors, steam, and oil/diesel) and supported by safety aids such as visual and audio signs and alarms, announcements and Personal Protection Equipment. The 'shortest' path is an optimised time value for egressing safely by minimising the cost and loss function based on local conditions and personnel status attempting evacuation. As expected, evacuation time duration is not precise, and the development of the framework presents a compelling case to evacuation planning.

The most significant benefit of the prediction framework is the ability to visualise the Network, which allows for efficient inspection leading to early assessment which can realise ship reconfiguration, and then quick recalculation!

Chapter 9 Characterisation of RTLS in Operation

Passenger ship onboard real time location systems (RTLS') are now coming into favour yet are not new (Hadsall, 2015) and (TheExpressWire, 2022). The size of the RTLS market has risen significantly for a variety of applications, including health, mining, warehousing, and industry. The means to use these systems in real time to help evacuees in difficult circumstances is to enhance personnel awareness and to supply guidance. Standard methods and approaches or current thinking do not cover these aspects.

An RTLS facility with the ability to send in real time data can find situation awareness trends, will result in a significant increase in passenger safety. Simple and robust tools that work in a real time are needed. A future RTLS system will provide directed safe path information to evacuees and promote self-decision making, while communicating with external participants. Evacuation supervisors or dedicated crew, in less stressful situations will interact with passengers, and share the moving story as the evacuation unfolds.

RTLS systems will use the results of the prediction algorithm proposed in this research, to provide path correction directions in real-time, in-situ, and with evacuees. The RTLS system will allow evacuees to make self-informed decisions about the route for escape, and at the same time, by checked by external systems.

9.1 Operational RTLS Systems

A myriad of systems uses RTLS technology to facilitate both location and movements of assets or personnel in mining, industrial, infrastructure, hospitality and logistics services. For example, the oil and gas industry in Canada employs a range of active radio frequency identification (RFID) tags for asset and personnel tracking by implementing it into the workers' helmets or worn tags on clothing, to track the locations of individuals in case of emergencies. This technology enables management to view whether, and how quickly, zones are emptied or filled during evacuations. However, even though it adds value to the oil and petroleum industry, this system simply checks personnel to ensure all are accounted for in an emergency, after the fact, it is not interactive (RFID Journal, 2013).

For shipborne systems, Vanem and Ellis (2010) present an evaluation of the cost-effectiveness of a passenger monitoring system based on RTLS technology for

implementation onboard passenger ships. This system can also detect and keep track of evacuees onboard the ship in emergency situations to provide crucial decision support to the Damage Control Centre (DCC). Even though it is assumed that it increases safety and evacuation ability, it comes at a cost. This paper concludes that it is not cost effective to pursue active RTLS technology for evacuation purposes. This conclusion, however, was bound by serious assumptions and uncertain estimates of the cost of active RTLS implementation. In addition, the cost of averting a fatality was assumed at $3 million based on the then current maritime safety decisions within the context of the International Maritime Organisation (IMO). Both these assumptions can now be challenged as the RTLS technology has matured greatly and competitively and the cost of averting a fatality has now to be calculated based on greater safety awareness in a maritime context.

As part of a large data collection exercise for large passenger vessels at sea (Deere, et al., 2008) detailed in one ship, that a total of 1,769 passengers were assembled over two days to collect passenger response time and movement data using video cameras and an infrared (IR) based position logging system. As part of this exercise, active RFID sensors were found to be inferior to the IR-based tracking systems which were better able to accurately track large numbers of individuals in high density crowds. The RTLS supplied reasonable read rates, but the performance of the IR system was superior in all cases.

Some new cruise liners have been introducing RTLSs. For example, the Royal Caribbean International line has introduced this technology to several ships (Parnyokov, 2014) in 2010, onboard the ship Oasis of the Seas. The application employed the Ekahau Company’s RTLS used Wi-Fi-based RFID tags in badges or wristbands, and an Apple iPhone, which accessed each tag's location on its screen displaying a map of the ship. The location information was transmitted to the iPhone via the ship's existing Wi-Fi vertices. The system enabled the iPhone user to send an alert when needed to those wearing the wristbands.

Some years later, in 2014, the Royal Caribbean International's newest cruise ship, the *Quantum of the Seas*, embarked on its maiden voyage with its passengers introduced to several RTLS-based features. These features included passive high-frequency (HF) radio frequency identification (RFID) ‘WOW band’ wristbands that could be used to unlock their staterooms' doors and make purchases onboard. The ship also adopted RFID luggage

tags, enabling guests to local area network to view the locations of their bags during loading and unloading.

The system was further developed and in 2018, the Mediterranean Shipping Company introduced and implementation of '*For Me*' mobile phones. The shipping company's system connects passengers and crew on board. Communication on ships with many international guests was made easier by improving life on board with the application including functions such as indoor navigation and proximity solutions. It even goes so far that parents who have their children looked after can find where they are at any time (MSC, 2022). This digital technology interconnects the passengers, the crew, and the ship systems. Passengers experience seamless, connected, and carefree time onboard. This novel RTLS system currently in operation does not extend to supplying a full safety system that can handle evacuation guidance; for that, a path prediction algorithm is needed.

The easy-to-use interactive touchscreens around the ship, the In-Cabin Smart TV and the application are all designed to help guests better relax and enjoy their holiday with family and friends.

In 2015, Hadsall (2015) submitted a US patent to provide a standard process for the detection of people onboard cruise ships. The Patent supplied a list of systems and procedures for tracking the locations of passengers on a vessel. Systems included a portable tag configured to be assigned to a passenger, with the tag encoded with a tag identifier. A number of tag readers were configured to be positioned at predetermined locations on a vessel, with each tag reader configured to read the tag identifier of the tag when the tag reader received a signal from the tag. The systems included a tracking component configured to communicate with the tag readers, and the tracking component configured to receive, from a detecting tag reader, a sign that the signal has been received from the tag. The tracking component was configured to decide a detected location of the tag based at least in part on the predetermined location of the detecting tag reader. A notification component was configured to send a notification including the detected location towards a user device. This process can be seen in Figure A 1.

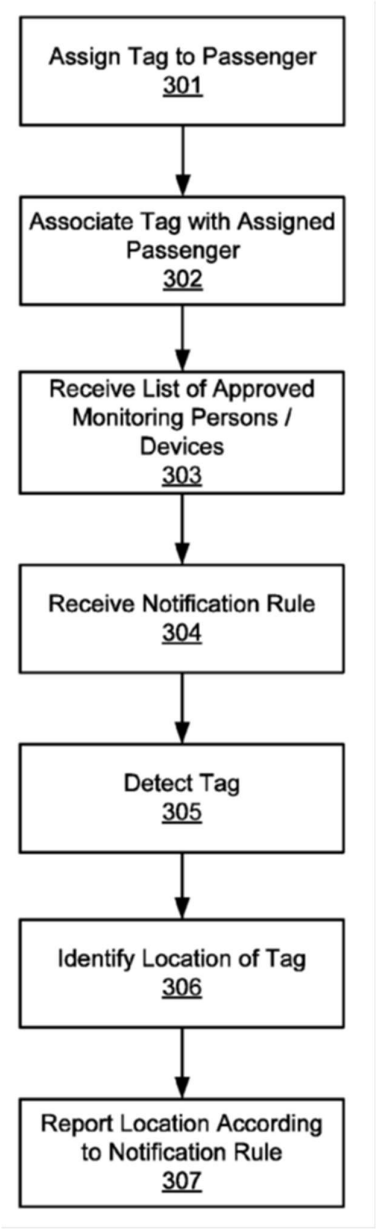


Figure 9.1 RFID Location Process

9.2 An Example of a Real Time Operational Scenario

To understand how a real time intelligent emergency simulation system may be used, a practical scenario in an operational environment is presented. The primary threat onboard ship are fires, flooding, or explosions as they are the commonest form of disasters (Bellas, et al., 2020).

A fire or other serious emergency which starts onboard ship is found and registered by the emergency control system (via smoke and temperature sensors) and reported to the ship's DCC. Damage control hardware units are fitted with active RTLS receivers and are independently checked via the DCC, which is part of the ship's intelligent emergency control system. This system is distributed throughout the ship to ensure it captures the ships topography and is safely integrated within the ships structure (hidden behind girders or frames).

Each passenger and crew wear a RFID tag that is checked by the RF receivers in the ship providing location and movement data to the DCC.

In emergency response mode, the damage control unit is also augmented by the wearing of specialised RFID tags. These tags register and check the number of crew fighting the fire, the locations, the ship's crew movements, and added sensors can be built into these tags that sense the average temperature, humidity, heat radiation, oxygen levels and even radiation. The data is transmitted via the RFID interface, carrying added sensor data to the DCC via the RF network. The more the supervisors interact with the damage control crew and understand the situation, the better their response.

The RTLS data, in real time (spatial and temporal) shows a view of the disaster areas, the not to access areas. This information is fed to a prediction module to forecast the course of the fire and the movement of the active participants. The RTLS data is constantly updated, the simulation is repeated in real time, as a function of time and space, detailing specific movements that better define the fire/flooding movement and dynamics and includes information on smoke density, toxic gases amount, temperature, fire/flooding spread, visibility, and alarm status. The firefighting supervisor assesses the continuously updated situation simulation in conjunction with personnel and equipment resources. In time, the Supervisor issues instructions to the in-situ damage control crew to either improve their firefighting efforts, or to evacuate the scene, or directs personnel to move to a safety point. With the help of the system, behaviour is extrapolated, and this is used to forecast directions.

The DCC supervisor has an intelligent alarm and voice communications system that shows the lowest risk firefighting option based on probable consequences, based on the prediction module updating progress. Persons onboard alike are informed on the situation. The supervisor issues commands to damage control units dealing with the disaster and

informs the ship's passengers and crew with notifications. Passengers are also informed with directions and knowledge of what is happening at any one time.

With the ship-wide knowledge of the emergency and supplemented by damage control experts, the DCC supervisor has a 'chessboard' control over the situation. Risk and safety consequences are minimised with greater confidence and influence over the damage control units.

For approaches to overcome evacuation risks, the use of real time scenarios supplies the context.

9.3 RTLS Features

As argued above, real time passenger location monitoring and communications is a significant step in bettering evacuation performance. A real time personnel location tracking system would overcome the deficiencies found in most ship emergency scenarios, including a more recent disaster on the *Costa Concordia* which occurred in January 2012.

During ship operations, simulations can be used a priori to augment the emergency awareness of the Damage Control Supervisor which typically can interactively check crew actions (movement, velocities) using a RTLS implemented by tags (or other) attached to personnel in low level deck compartments of ships or in buildings. Such RTLSs are becoming widespread and are plentiful (see Figure A 2).

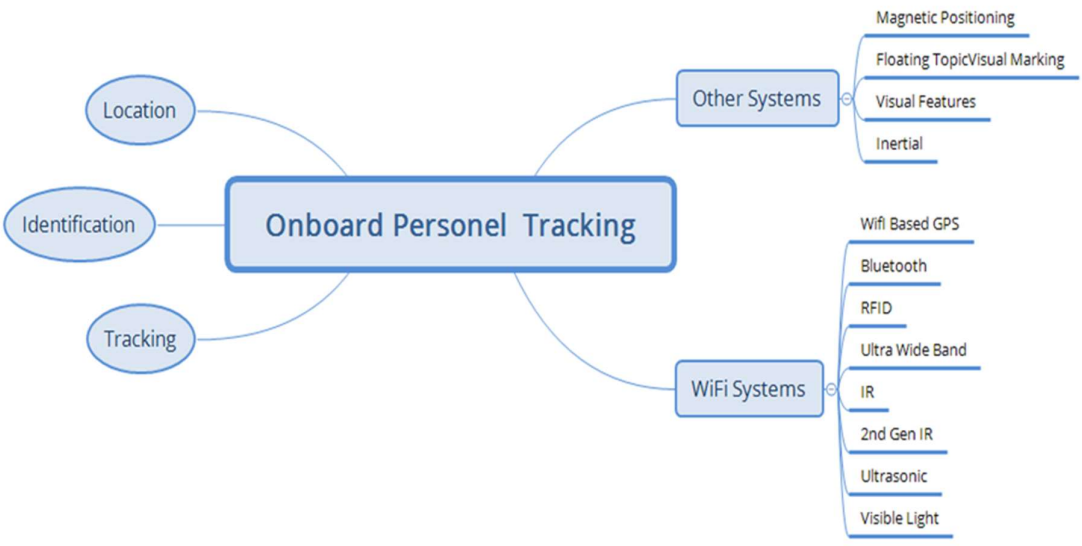


Figure 9.2 RFID Location Process

For Navy use, RTLS tags can be worn as a badge or embedded in a helmet. These systems are designed with best practice in mind and the International Organisation for Standardisation/International Electrotechnical Commission, ISO/IEC 24730 Information Technology – a RTLS series of standards support that have been adopted to fulfil that need (ISO/IEC, 2014). Gathered real time data can be uploaded to the central computing facility for the evacuation simulation to be updated with real time information. Issuing orders to in-situ personnel will dramatically enhance their likelihood of success of firefighting and/or evacuation. As the systems is aware of all passenger and crew locations and automatically logged as the emergency unfolds, roll calls are not needed. This coupling with prediction of arising circumstance, an intelligent alarm and emergency voice evacuation system supplies a significant benefit in adaptive disaster management making a real contribution to the disaster management on Navy or commercial ships. Here speed and efficiency are critical ingredients to track chaotic events in real time.

Active detection devices coupled to optimised prediction capability opens a myriad of possibilities that supply a less risky evacuation course because it is being supervised as the situation unfolds in real time. This approach takes away the focus for evacuation away from the ship designer to the actual disaster controller and has the benefit of lessened use of sophisticated tools which are bolstered by vast amount of test and data support. The prime benefit is that it allows for decision making to be taken away from the stressed damage control party; instead, supervisory staff applies awareness, thinking processes,

in-situ awareness and visual alerts and communication to minimise human error. This approach will expand the crew's escape ability and at the same time, minimise harm.

This is an important outcome of RTLS potential expansion into a full evacuation prediction system. Implementing easier and efficient prediction overcomes the existing prediction gap with current predictions tools; these tools are better utilised in research institutions and not in an industrial ship acquisition program. However, current evacuation predictions can be used to good effect if they are used to support lower-level localised detail in the design of ships. Most importantly, the data can be captured and used to supplement emergency data.

9.4 Disaster Representation

For the Navy context, the ship evacuation management system defines the processes of decision making related to the initiating events, the response, the evacuation, and the recovery sequences. Decision making is defined as the process of making an informed choice among the alternative actions that are possible during an evacuation. It also involves the commitment of resources from the initiating event to the safe embarkation of the crew and is dynamic in nature.

To understand what impact RTLS has upon the functions of a real time ship evacuation management system, Figure 9.3 supplies a top-level description, derived from the current literature, of a system having Radio Frequency Identification (RFID) tags supplying real time personnel and surrounding conditions. The key component of the system is the planning activity related to developing a path prediction solution, characterised by the Required Safe Egress Time (RSET) compared to the Available Safe Egress Time (ASET) to decide the safe margin for egress. The key decision-making activity is the sensing function coupled with the feedback loop to check the safety margin continuously.

Figure 9.3 shows a typical control process finding system elements that are needed to undertake real time evacuation planning in situ. It forms feedback loops to utilise active data capture, status monitoring and decision-making process.

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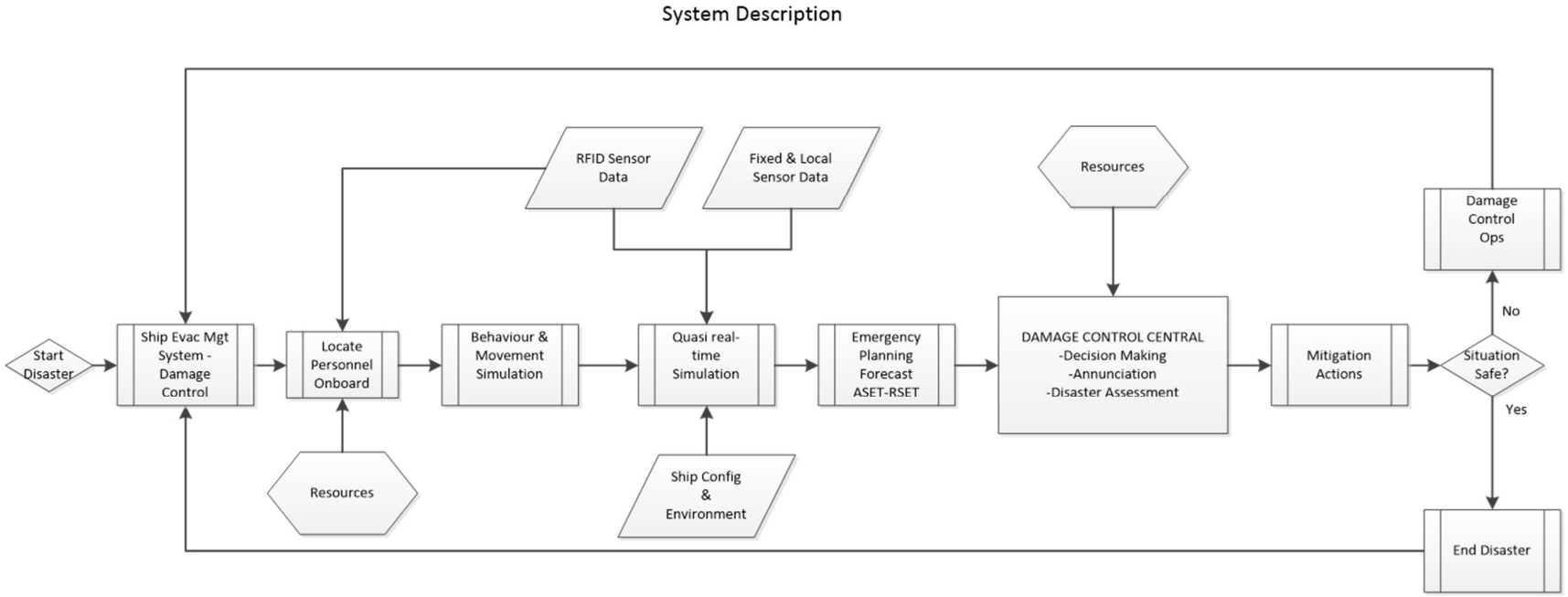


Figure 9.3 Key System Functions

9.5 Concluding Remarks

The literature research has uncovered that the current state of prediction for real time systems that are insufficient to expand the RTLS to become useful. A new approach and system are needed to enhance the RTLS, to handle the nuances of dynamic effects and safe evacuation, and in doing so, betters situation awareness and supplies a firmer ground for safe evacuation decision making.

The potential solution to overcoming the deficiencies is described in this thesis. Further applications of RTLSs have been conducted as academic research specifically for asset tracking of goods and parcels (Tahir, 2019). However, research into persons tracking on ship is limited. One aim is to develop an RTLS system using a pro-active safety approach that incorporates route optimisation, communications, and instruction.

While the person tracking problem has been solved by industry, what is missing is route optimisation algorithm technology to supply safe path egress predictions.

Chapter 10 Conclusions and Future Work

10.1 Achievement Overview

Ship disasters in the last 100 years or so have resulted in a large number of deaths. Even though ship designs of the same period have included provisions for safe evacuation by including lifeboats and safety appliances to aid the evacuation. Methods of evacuation prediction have been developed and used in the design of ships, but this research has concluded that the use of these tools has resulted in the appreciation that these tools cannot predict an actual event. To improve this situation, credible alternative means are needed that expand the view of simulation. To that end, this Thesis has presented framework, methods, and processes to get a better understanding of the evacuation process. This can be understood because methods, approaches and naval improvements have occurred over the last 100 years that can make the situation more revealing and tenable in predicting a disaster. These missing elements point to characterising the ships architecture and the means to account situation awareness and the causal nature in deciding an outcome.

This Thesis explains that these innovations, studies, lessons learnt, and knowledge have uncovered complexities that need to be overcome, and therefore, the methods presented ,herein have taken note of pinpointing several added factors that must be included to make better evacuation predictions.

The work herein focussed on the common denominator to find a better means to predict evacuation time in a complex ship, that is, to find a simple, robust but more accurate means to predict evacuation in a broader context of soft skills adopted for engineering for the design of ships, or to serve the larger purpose of developing a real time location system. The literature search confirmed that current methods are many, complex, resource heavy and deterministic and, take large amounts of computer resources. In their current state, it would be very difficult to be employed in Real Time Location Systems (RTLS'), and to provide well studied concepts and requirements determination because they don't lend themselves to be iterative and interactive design tools.

This study has pointed out that for design purposes, prediction preference was to use network analysis and Graph Theory as the basis for this work. A coordination of applicable methods was brought together focussed on networking which considered the architecture interactions and its emergent properties. Human behaviour was implied in

dealing with the evacuee's situation awareness, his experience and individual capability and his training.

This study achieved the integration of approaches, tools and thinking into one logical method (and tool). For design purposes, the prediction tool results showed successful parity with IMO Guidelines, in particular with the IMO's MSC.1/Circ. 1533 for the investigation of suitable paths in a timely matter.

The developed tool highlighted substantial difficulties of the method to predict an actual event, for example, scenarios only considered day night events, whereas the nature of the cause of event, i.e., fire, flooding, or structural damage lays the context of the prediction analysis. Nevertheless, the Guidelines achieve an outcome, but are limited in that they are difficult for users to automate path optimisation and selection because the analysis is conducted by hand. In the final scrutiny, the method promoted by the Guidelines make visualisation of optimum constrained paths very difficult to deal with.

Of significant mention was the ability to visualise the spaces in the ship and how they were connected. Changes could be made within seconds and then the model re-run to present the changes. This interactive method is probably its most useful aspect, leading the way to conduct studies based on many data points.

If prediction is executed in real-time, the problem becomes easier as these variables are captured and implied in their in-situ movements. Such a system will benefit the forewarning of safety information concerning annunciation, incorporating evacuation signage and providing situational 'knowledge' to evacuees to better visualise of the emergency state. These benefits can be realised in the implementation of a network-based evacuation prediction model. Of equal importance is that the network model transforms the visual into mathematical language, which allows the user to conduct optimised prediction studies. The ability to visualise the changing of topography, the spatial quantities, the packing density, the obstacles, the crowding aspects, make for an idealised method of evacuation; it's not a statis idea. Most importantly, the model supplies the opportunity to change the argument by focussing on route selection based on causes, environments, risk, or whichever constraint is presented.

In contrast, several weaknesses are clear. This includes the search for maritime data related to the intricacy of aspects of the model, for example, the assumption that

behaviours can be treated as an uncertain parameter and the implication that it can be defined by movement data. Also, the correlation between prediction and situation awareness requires more specific attention to be practical, a study in itself. It is also uncertain how much closer this prediction method can achieve in the real world.

The prediction is a considered and rational approach to enhance understanding through visualisation, reworking, managing evacuee flow, analysing data outcomes, and presenting solutions at hand. The introduction of probability theory into the model allowed the user to embrace uncertainty and use it in whatever context.

10.2 Research Interest

This research study has gained momentum of the significant interest shown in the presentation of a paper in the prediction of evacuation dynamics, as evidenced by the publication of this work in the *International Journal of Maritime Engineering* (Capizzi, V. & Marian, R., 2021) and noted in the List of Publications. The research outcomes substitute extensive prediction methods applied to maritime ships and will have a significant risk reduction impact on safety analysis due to efficient and flexible techniques using linear programming. This research mitigates levels of uncertainty and complexity in a simplified manner by adopting stochastic modelling and analysis of evacuation data.

10.3 Detailed Observations

The research discussed herein investigated the feasibility to conduct an evacuation simulation using established and simple Excel spreadsheet approaches using flow balance criteria and specific path constraints. The evacuation simulation is based on a linear modelling representation of the vertices/edges and uses an iterative Excel Solver® numerical solution to solve the 'shortest' path problem. Graph modelling is an excellent and applicable technique to calculate evacuation simulation. It is well suited to optimisation and reconfiguration incorporating user-friendly methods to make changes. This is a significant and innovative advance to the state of evacuation analysis.

The prediction method brings together tried and tested techniques which have become adaptable to the prediction model explored herein. This is a novel approach.

The model supplies both movement (time and path) and traffic congestion information on the selected shortest path. This information is best utilised in both systems feasibility studies for ship design purposes (including Navy ships) and/or validation analyses to

characterise evacuation performance of existing ships using an expedient method of analysis. The model produced the desired expected outcomes, namely, the determination of the shortest path.

The nodal representation allows the user to have a 'world view' of the evacuation path topology and investigate obvious path constraints. Each path should require at least two choices for movement in case of evacuation failure. In some cases, however, this may prove to be impractical.

Traffic delay plays an important part in the design layouts, supported by visualisation and network metrics. Thus, the aim was to introduce a design KPI which supplied a simple tool to decide the probability of delay.

Each execution is confirmed by flow balance and capacity constraints. This is an important aspect of the validation of the mathematical nature of the model.

The introduction of Monte Carlo analysis is another useful tool that provides the flexibility to consider the uncertainty of movement (person's velocity, age, and disability; and, ship motion, lighting levels, gaseous hazards) with human behaviour in the calculations. Defined as probability distributions, they can be added to obtain a best likely outcome and a realistic representation of evacuation. This is an advanced means to tackle evacuation uncertainty but is best implemented when applicable data is obtained to constrain the probability of events.

A solution cannot be found if persons have no alternative path to reach the destination. Perhaps this is its greatest contribution of this research and quickly identifies a potential safety issue which can be addressed and eliminated at an early stage of the design. With the capability to re-configure paths (edges), it can dynamically assess damage or fire fronts, or even water ingress scenarios by incorporating environmental transients. This capability can be used to configure evacuee movements in real time and can incorporate the implementation of latest and future means of aiding evacuation.

The network approach adopted for evacuation modelling is a general technique that can be used to optimise specific design parameters – for example, optimising corridor widths or compartments for a specific evacuation time. This is adaptable as needed to better the strong capability and contribution of the research.

The method as compared to the IMO's Guidelines, via the implementation of the case study highlights the major differences relate to approach, the IMO's being deterministic and this approach which is stochastic. Also, the MSC method is dependent on the user's involvement in deciding the best path. In contrast, the research solution is decided by algorithms which are strongly adept to running many assessments very quickly. The research approach is quite scalable, supplying consistent results no matter the size and complexity. The research approach greatest strength is that it is visual, making it easy to support understanding, adaptability, availability, and scalability as required by the designer.

10.4 Recommendations for Future Work

The research into this method was not conducted to find a replacement to the existing plethora of specialist tools that have been developed over a long period of time. Rather, the aim of this research was to propose and develop an alternative and complementary robust methodology and framework that can be used simply and accurately to provide a system view of evacuation which is aligned to the standard practice and guidelines presented in MSC 1533. This research has met this aim.

It is recommended that the methodology be further developed in various ways. First, the methodology can evolve to increase its level of realism even more by eliminating the simplifying assumptions. Second, the simulation should be extended to identify all the potential paths from source to sink and to rank them, and then prioritise them. This extension will discover potential personnel pitfalls along the pathway. Third, the tool can discover transient phenomena during enforced damage situations and simulate path dynamics to develop a time-based description of the damage scenario as it unfolds; this requires a data mining to supplement the tools accuracy and credibility. Fourth, network metrics can be explored for a means to rank networks by their degree of network density and their influence on connectivity.

Human behaviour needs to be further improved and investigated to be more practical and accountable for the prediction. The methodology should give insights into alternatives with the view to uncovering the worst and best performance result.

The network view of systems can be used to analyse relationships, not only for paths, but for systems, or system of systems. This approach allows to use simplistic optimisation

techniques to solve even more complex systems. This simplification is the real potential of this work. It opened the mind to abstraction of systems analysis combined with physical entities relating to human traits.

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APPENDIX 1 - STATEMENT of AUTHORSHIP FORMS

University of South Australia

Statement of Authorship

Title of Paper	A Stochastic Network Approach Toto Modelling Ship Evacuation.
Publication Status	☑ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details Relevant reference details	International Journal of Maritime Engineering, Oct-Dec, 163, Part A4 (695), pp. A-19 to A-34.
PRINCIPAL AUTHOR	
Name of Principal Author (Candidate)	Vincent Capizzi
Contribution to the Paper Brief description of your work in this publication	Principal Author outlining research topic concerning ship evacuation. It describes the approach and technical details of an approach and algorithm used to determine minimum time to evacuate, A case study is included and is verified against current IMO guidelines.
Overall Percentage (%)	80%
Certification	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.
Signature *Signatures will be redacted by the Library at the time of publication*	Vincent Capizzi Digitally signed by Vincent Capizzi Date: 2023.06.30 16:03:33 +10'00' Date
CO-AUTHOR CONTRIBUTIONS	
By signing the Statement of Authorship, each author certifies that: I. the candidate's stated contribution to the publication is accurate (as detailed above); II. permission is granted for the candidate to include the publication in the thesis; and III. the sum of all co-author contribution is equal to 100% less the candidate's stated contribution.	
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% Contribution to the Paper	20% Editing and technical review
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Statement of Authorship

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PRINCIPAL AUTHOR	
Name of Principal Author (Candidate)	Vincent Capizzi
Contribution to the Paper Brief description of your work in this publication	Development of the methods and approach to determine the minimum time to evacuate from a ship in an emergency situation.
Overall Percentage (%)	75%
Certification	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.
Signature Signatures will be redacted by the Library at the time of publication	Vincent Capizzi Digitally signed by Vincent Capizzi Date: 2023.05.30 16:03:11 +10'30'
Date	
CO-AUTHOR CONTRIBUTIONS	
By signing the Statement of Authorship, each author certifies that: i. the candidate's stated contribution to the publication is accurate (as detailed above); ii. permission is granted for the candidate to include the publication in the thesis; and iii. the sum of all co-author contribution is equal to 100% less the candidate's stated contribution.	
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% Contribution to the Paper	10%
Signature Signatures will be redacted by the Library at the time of publication	Romeo MARIAN Digitally signed by Romeo MARIAN Date: 2023.05.30 23:40:36 +08'00'
Date	
Name of Co-Author 2	Prof Peter Campbell
% Contribution to the Paper	15% Signature unable to be obtained due to health issues.

University of South Australia

Statement of Authorship

Title of Paper	SYSTEMS GRAPHING ALGORITHM METHOD FOR SHIP EVACUATION STUDIES
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Name of Principal Author (Candidate)	Vincent Capizzi
Contribution to the Paper Brief description of your work in this publication	Developed the Conference Paper while conducting research in my filed of interest
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