A STOCHASTIC NETWORK APPROACH TO MODELLING SHIP EVACUATION

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SUMMARY

This paper presents a development of a novel, efficient, and robust tool to conduct evacuation from maritime ships using multi-commodity network theory and graph search techniques. MSC/1533 (IMO, 2016) presents guidelines to conduct simplified/quasi-advanced analysis methods for the evacuation analysis of ships. The IMO techniques describe a prescriptive approach and don't consider path variabilities or uncertainties associated with the dynamic nature of the evacuation environment. To enhance the work presented by the IMO, a linear programming multi-commodity graphing solution has been developed and implemented in Excel. This model is based on network and graph theory and specifies basic passenger characteristics, simulates ships geometry and specifies path constraints. The simulation determines the shortest route to the nearest safe point/muster station. Monte Carlo is used to characterise model uncertainties in the simulation. Initial experiments indicate this technique is feasible. As a Systems Engineering tool, it can be used in trade-off studies to finalise ship layout design and identify path delay/choke points and can be used to rank evacuation performance of existing ship configurations.

NOMENCLATURE

ABM	*Agent Based Modelling*
Edge	*A link that connects Nodes in a network.*
FOM	*Figure of Merit*
IMO	*International Maritime Organisation*
MC	*Multi-Commodity*
MSC	*Maritime Safety Committee.*
Network	*A system of nodes connected by edges.*
Node	*Identified area with physical dimensions such as compartments. corridors, stairs etc.*
NodeXL	*MS Excel Add-on for plotting networks.*
Robust	*The capacity of the algorithms to consistently find a solution to evacuate people when a solution exists.*
RO-RO	*Roll On/Roll Off (ships).*
SE	*Systems Engineering.*
SOLAS	*Safety of Life at Sea (IMO).*
V&V	*Verification and Validation.*

1. INTRODUCTION

1.1 MODELLING STATE OF THE ART

In the pursuit to better the simulation tools for emergency evacuation, there is a lack of uncomplicated tools that ideally suit inquiry and assessment that underpins systems engineering feasibility studies and the development of ship concepts and design.

There is a plethora of evacuation models on the market (Lee, et al., 2003) that handle complex ship configurations using advanced techniques such as Agent Based Modelling (ABM) (Lang, et al., 2014). ABM techniques employ a bottom up approach in which each agent behaves in accordance with a defined set of rules. Their interactions are played out and emergent behaviours are identified which are not intuitive, see (Bonabeau, 2002) and (Epstein, et al., 2011). Literature citations referring to the benefits or otherwise of ABM include (Bonabeau, 2002), (Epstein, et al., 2011), (Zhan & Chen, 2006). However, none of the references refer to the specific area of ABM for naval ships.

These tools are often derived from the building, infrastructure or bridge design (pedestrian (flow) domains to serve the interests of building escape or traffic simulations, providing the bulk of the movement data available.

Adapted to ships, these tools offer a useful tool for the ship designers and naval engineers in a ship acquisition program. Mostly, these tools require significant investment in time, materials, resources, knowledge and training; they often become a significant work packages of the acquisition program requiring specific project management and resource oversight. This is especially true when they need to be applied iteratively to an evolving structure.

A summary of well-known software tools adapted for ship designs include maritimeEXODUS (FSEG, University of Greenwich, 2020), AENEAS (Meter-Konig, et al., 2005), EVI (Brookes Bell, 2020), IMEX (Jin-Hyoung, et al., 2004) , DEMON (Boulougouris & Papanikolaou, 2002) and VELOS (Lang, et al., 2014). AENEAS and maritimeEXODUS are grid-based models in which the floor plan of the ship is divided 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 determine confidence in the final results.

Maritime EXODUS is a flexible and useable tool that maps the layout topography, making it useful for evacuation studies; it has been used for naval studies in the evacuation modelling of QE Class Aircraft Carriers (Andrews, et al., 2008) and as a PHD Thesis by (Casarosa, 2008).

An example to tackle the simplification of the growing complexity of tools was the development of a Master's thesis (Hifi, 2017) that investigated the use of ABM software EVI and the analysis technique, the Batch Non-Homogeneous Poisson Process (Batch NHPP). The results were encouraging; however, the simulation suffered the same issues mentioned above, i.e. high degree of complexity, human and computer resources and schedule and computer time expenditure, taking significant time allocated to the Master's degree to develop the thesis.

There is a requirement that 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. These phases are the most important part of the acquisition. To meet the requirements of SE efficiently and expeditiously in this specialist domain, a simple but accurate means is required to frame the ships evacuation performance and support the rest of the SE acquisition and support lifecycles. The work presented herein allows for such an opportunity.

Similarly, using alternate existing ships to support procurement of ships and requisite safety aids should be placed in the hands of non-specialist resources to make recommendations. The approach presented herein allows for technical supply authorities and their associated shipping agents to use a similar approach presented herein.

The development of this application is viewed as a radical departure to the standard methods/approaches currently available to provide simple and fast tools. This research is needed because evacuation modelling should be used by non-specialist technical resources using efficient, high quality and expedient tools.

This research is innovative in that it uses technical data primarily from Industry in conjunction with a combination of established linear programming techniques to optimise escape routes, supported by Monte Carlo simulation to identify the uncertainties in the solutions. Monte Carlo simulation is a risk 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 time of movement. It then calculates results over and over, each time using a different set of random values from probability functions (Kroese & Botev, 2014); this is the major difference to most of the well-known software tools on the market today.

1.2 BACKGROUND

The concept presented herein is based on Leonard Euler, who in 1788 constructed the first graph to solve the famous mathematical puzzle for the Königsberg bridges (Boonchev & Buck, 2005) and a modified Traveling Salesman Problem (TSP) with set start and finish cities. An algorithmic model solved the TSP and is based on network theory and includes nodes and edges exhibiting a network like structure typically referred to as a Graph algorithm. The TSP is well known and an important combinatorial optimization problem, one of the most studied problems in computational mathematics (Hahsler & Hornik, 2007).

Network Theory and Science has been used previously to model warship recoverability modelling (Bain, 2006) and (Gillespie, 2012). Also, network theory has evolved into a tool to investigate not only topographical features, but relationships in systems such as electrical or fire fighting systems. The authors showed the usefulness of early ship design with the ability to simply model ship systems (Rigterink, et al., 2014).

In previous papers (Capizzi & Marian, 2019) and the INCOSE/SETE Virtual Systems Forum (Capizzi & Marian, 2020) the Authors concluded that:

- The premise postulated by J. W. Gillespie that the relationship between graph theory and network science in his PhD thesis (Gillespie, 2012) is valid.

- Evacuation paths can be modelled by using optimised linear programming network techniques (graphing algorithms) constrained by cost and path capacity or difficulty to determine the best path in the minimum amount of time. The "shortest" path is defined by an ideal passage time for safe evacuation. Optimisation minimises cost and loss function, which is based on local conditions and personnel route capacity. The data used to determine passage velocity is based on the building industry and covers a myriad of circumstances too numerous to present and uncertain to be identified as deterministic; this is the nature of the data that has been used in this study. This characteristic allows one to consider probability to determine a likely evacuation performance based on stochastic processes:

- Multi-commodity graph (network) modelling is an appropriate technique to calculate evacuation time. It is well suited to evacuation analysis as it can be adapted to run as an interactive optimisation algorithm 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. Various evacuation restrictions 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 identify potential death traps in a design or find alternative paths to reach the destination. Perhaps this is the tools greatest contributions.

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

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

- The ship layout can be represented as a modified TSP with paths, constraints and capacities along modelled edges.

- The ship is represented by a routing directed network using nodes describing transition points comprising compartments, rooms and edges comprising corridors, passageways, stairs.

- Adopting a linear programming model allows for degradation constraints with time. There is a notable difference with the TSP: the start and the end of the travel are different and defined for each space.

This paper covers the above points and presents a fresh schema for ship evacuation using Multi-commodity flow algorithms. It builds on the previous work by introducing a first order hydraulic model to determine flow progress and delays and represents quantifiable evacuation tool that can support an engineering approach, judgement and analysis. Hydraulic models are based on a simple flow constrained by a boundary and described by a set of equations. Escapees 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" (Gwynne & Rosenbaum, 2016) and path constarints.

1.2 EVACUATION PREDICTION FRAMEWORKS

Fundamental to the evacuation system is the means to predict the safest and shortest route for humans to the safe evacuation point; mathematical concepts can be used to define and control the exit strategy. The solution lies in the definition and analysis of spatial properties such as specific topological, geometric or geographic entities. Modelling techniques may use mathematical representations of spatial properties using nodes and edges to define the spatial characteristics and then applying cost functions to characterise the path length and time. More complex representations can utilize 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 and can react, interact and modify their environment while seeking safe objective) (Macal & North, 2007).

Literature on specific mathematical network techniques for ship evacuation is limited; (Chang-Wu, et al., 2013) presents a deterministic graph search model that is used to simulate different evacuation scenarios using a nodal flow method coupled with a minimized cost model to determine the shortest path. The modelling has stringent assumptions that limit the outcomes to a purely mathematical exercise; similar in approach to our research but limited in outcomes.

1.3 MARITIME PRACTICE & CONTEXT

The International Maritime Organisation (IMO) is a United Nations agency responsible for the regulation and safety and security of shipping; marine evacuation is governed by incorporation of Safety of Life at Sea (SOLAS) guidelines (International Maritime Organisation, 2020).

SOLAS Regulation II-2/28-1.3 provides the guidelines for evacuation of passenger ships and high-speed passenger craft (Dongkon, et al., 2003). MSC/1533 (IMO, 2016) is the latest revision in a series of similar guidelines dating back several years. MSC/1533 presents both simplified and advanced methods to analyse evacuation by using typical benchmark evacuation scenarios and relevant data to determine evacuation performance of roll on - roll off (RO-RO) and other ships. Most data and parameters stated in the guidelines are based on well-documented data originating from the civil building industry. The evacuation analysis objectives for existing or new design ships is to identify congestion points and/or critical areas providing recommendations as to where these points and critical areas are located on board; These guidelines provide performance criteria in terms of the total calculated evacuation time compared to the allowable evacuation time.

The MSC/1533 evacuation performance standard is defined as:

$$1.25\,(R+T) + 2/3\,(E+L) \le n$$

where;

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

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

R is passenger response duration – for purposes of indicating a benchmark, should be 10 mins for the night time scenarios and 5 mins for the day time scenarios: this could be stochastically derived based on available data.

T - is the total travel time, as calculated.

For the research presented herein, a figure of merit (FOM) is defined to determine route option effectiveness, in accordance with the performance standards:

$$FOM = ((1.25\,(R+T) + 2/3\,(E+L))/n.$$

The prime objective of this research is to confirm the use of multi-commodity analysis is a feasible method to solve evacuation cases at a high-level system view. This provides an initial Systems concept on ship layout and highlights obvious issues for evacuation.

2. APPLIED EVACUATION ANALYSIS

2.1 THEORY & ALGORITHM

Multi-commodity flow modelling (MIT, 2013) is a network flow

representation of multi-source and sink identities that consider demand and capacity fluctuations.

A common scenario of a network-flow problem arising in industrial logistics concerns the distribution of a single homogeneous product from plants (origins) to consumer markets (destinations). The total number of units produced at each plant and the total number of units required at each market are assumed to be known. The product need not be sent directly from source to destination but may be routed through intermediary points reflecting warehouses or distribution centres. Further, there may be capacity restrictions that limit some of the route edges. The objective is to minimize the variable cost of producing and shipping the products to meet the consumer demand.

Conceptually similar, passengers from locations in a ship (sources) are required to egress to a Muster Point/Evacuation Assembly Area just prior to evacuation (sink). The total number of passengers to assemble are known. Passengers do not need to travel directly to the Assembly Area but can take alternate routes to facilitate efficiency and minimise travel time. Passengers can also move in a contra direction to model ship evacuation process or finding life jackets stored in alternate locations. It is also known that routes have capacity restrictions due to specific flow (persons/metre/sec) or route widths. The objective is to minimise the travel time (Cost) and ensure all passengers reach their destination.

The modelling is characterised by (Society of Fire Protection Engineers, 2019):

- Specific flow restrictions along edges and secondly, cost assigned for each edge, i.e. the time duration to travel along edge including delays due to traffic.

- edge capacity, the sum of flows across an edge does not exceed its capacity requirements.

- flow conservation at the source and sinks, i.e. Inflow demand equals outflow supply; and

- flow conservation on transit nodes, flow entering a node is the same that exits.

A network comprising nodes and edges has many solutions and hence, one may optimise the flow to correspond to minimising a cost or a capacity. Therefore, the research focussed on determining the one set of paths that corresponded to minimal time required for traversal. For a minimum – time flow problem with n nodes:

xi j = Number of passengers traversing from nodes i to j using edge i– j (MIT, 2013)

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

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

Networks may have the following properties that are meaningful to a Naval ship (Hevey, 2018):

- Degree: degree is defined as the number of paths/connections incident to the node and infers node flexibility in terms of route/space connectivity allowing more path choice.

- Closeness: the closeness index quantifies the node's relationship to all other nodes in the network by considering the indirect connections from that node. In this case, other spaces/routes in the ship layout might provide alternative routes.

- Eigenvalue Centrality: Extent to which a connection to a busy route/space can be more important than a connection to a lone route/space.

- Clustering: the extent to which a node is part of a cluster of nodes can be estimated. The local clustering coefficient C is the proportion of edges that exist between the neighbours of a particular node relative to the total number of possible edges between neighbours.

There are numerous publications in the field; multi-commodity modelling is a universal approach that can also be adaptable to many industrial problems (MIT, 2013).

The following observations are made:

- Network models are special structures in linear programming, making them efficient and effective.

- The approach presented is simply derived from specializing the rules of the simplex method to take advantage of the structure of network models and to provide optimisation capability (Wright, 2016).

- The algorithms are extremely efficient and can find the solution of a large (ship) network model using a special linear-programming procedure; ideal for the complexity of ship geometry and human dispersion, and

- This technique is modelled and implemented in MS Excel with the Solver add-in (Frontline Solvers, 2020), which deals with optimization, simulation, and providing stochastic solutions.

2.2 MODELLING THE SHIP

The Ship used to illustrate the algorithms and demonstrate the capability of the proposed methodology is the 245 ft square rigged Tall Ship, Caledonia, with the specifications and as shown in Figure 1 and 2. The Vessel Type is a Passenger Carriage, Sailing; Flag, Canada; Class - SOLAS for International Trade by Transport Canada and completed Retrofit in 2008.

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Table 1. Ship Dimensions

Specification	**Value**
Length Overall	245ft / 74.68m
Beam	30ft / 9.14m
Draught	16ft / 4.88m
GRT	810 Tonnes Class
Deck	4x(Tank Top, Lower, Main, Upper)
Rig Height	131ft / 39.89m
Crew	20
Passenger	75
Life Rafts	12xVIKING 25DKF+ life raft, iaw SOLAS/MED.
Rescue Boats	2xNarwhal SV 400
Ships Tenders	2xNarwhal HD 580

Figure 1. Tall Ship Caledonia;

The Deck Plan is shown in Figure 2.

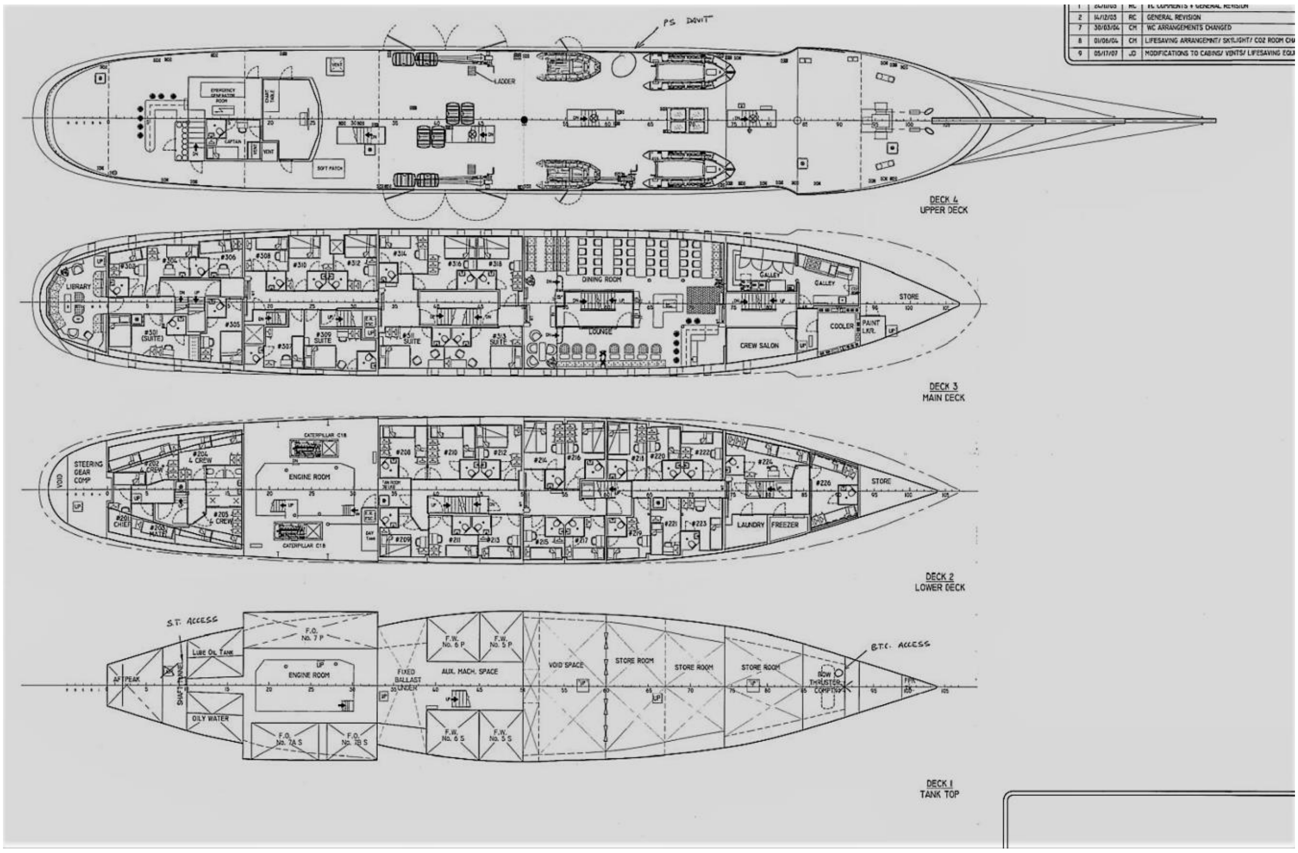

Figure 2. Caledonia Deck Plan

3. FACTORS THAT IMPACT EVACUATION MOVEMENT

Calculation of egress is sensitive to overall path characteristics such as geometry (path impediment(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, others are ship characteristics. The analysis presented looks at ship characteristics which can be quantified and modelled.

One of the most significant aspects of evacuation is traffic; this causes delay and increases risk. For design purposes, the model is best used to identify 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 identified in the path.

The approach used for estimating evacuation delay is to use hydraulic analogy, a process by which traffic is simulated as “abstract flows”. Another approach considers the behavioural aspects of the people. 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. The speed on stairs depends on stair geometry.

4. APPLICATION OF EVACUATION MODELLING TO CALEDONIA

MSC/1533 provides assessment scenarios for this analysis. For this assessment, the primary Night Case 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 provide recommendations.

- The performance standard for the night case is assumed to be 60 mins, as for RO-RO passenger ships.

- The example ship is based on an existing operational ship and comprises 4 decks with connecting corridors and stairs.

- A network diagrammatic view is presented in Figure 3 as an associated “hydraulic diagram”. It does not represent a dimensional/length quantity; nodes are represented to depict connections only. The layout follows a layered graph drawing or hierarchical graph drawing in which the vertices of the Caledonia’s directed graph is shown as horizontal rows or layers with the edges generally directed downwards, as per as Sugiyama-style graph (Sugiyama, et al., 1981).

- The corridors connect to doors, stairs or openings; the goal is to reach the Muster Station on Deck 4.

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

- Corridors specify the number of crew or passengers that occupy the corridor space at a specific time as a distribution, comprising 95 passengers and crew in total.

The performance standard is stated below. It defines the important parameters and puts into perspective the expected conditions and evacuation response results.

To display an enhanced perspective of the ships' evacuation geometry, a node and edge (vector) notation is used to represent the geometry and the direction of flow; as required for a forward search graphical algorithm, as shown in Figure 3 below; Note node 1Store1 to 1Store2 shows a loop edge.

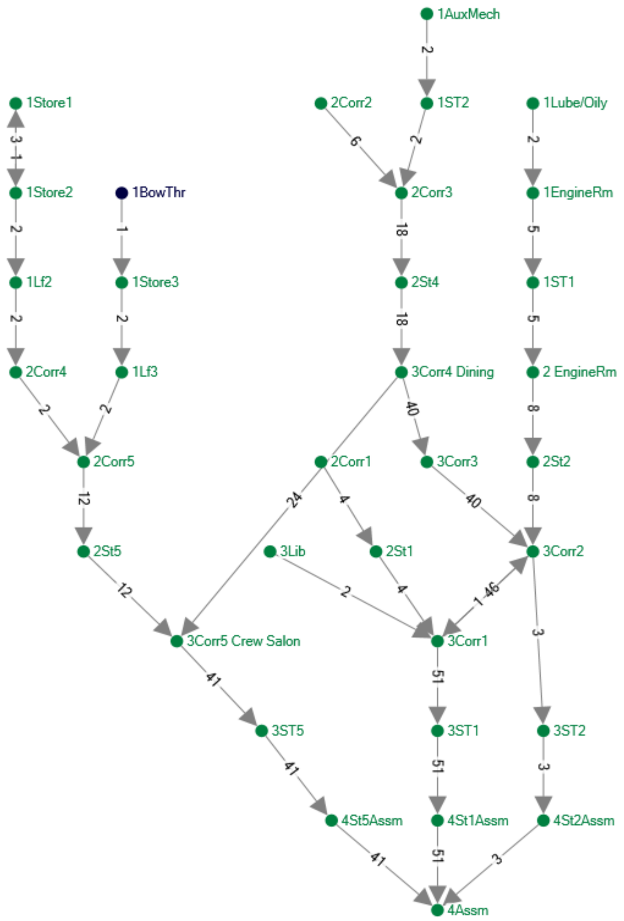

Figure 3. Network Representation of Ship Topography

Table 2. Selection of Compartment Dimensions (Approx.)

Compartment	Type	Room length dir. of flow (m)	Room width across dir. of flow (m)	Area m^2	Entry Effective width (m)	Exit Effective width (m)
1AuxMech	Room	10.20	3.22	32.84	1.00	0.84
1BowThr	Room	12.00	3.00	36.00	1.00	0.84
1EngineRm	Room	8.00	5.00	40.00	1.00	0.84
1Lf1	Stair	0.75	0.75	0.56	0.75	0.75
1Lf2	Stair	0.75	0.75	0.56	0.75	0.75
1Lf3	Stair	0.75	0.75	0.56	0.75	0.75
1Lube/Oily	Room	3.66	1.50	5.49	1.00	0.84
1ST1	Stair	3.00	0.85	2.55	0.80	0.80
1ST2	Stair	3.00	0.80	2.40	0.80	0.80
1Store1	Room	3.50	7.00	24.50	0.60	0.60
1Store2	Room	3.50	6.00	21.00	0.60	0.60
1Store3	Room	3.50	5.50	19.25	0.60	0.60
1Void	Room	4.00	8.00	32.00	0.60	0.60

The label refers to the location onboard ship, i.e. in the form "NumXXXXNum"

where
"Num" refers to Deck Number.
"XXXX" refers to description of space.
second Num refers to the item number off.

Example, 1Corr2 refers to Deck 1 and Corridor 2; ST refers to Stairs; Lf refers to Store Lift. Table 2 shows a selection of input data; dimensions are approximations.

The following observations are made:

- A 2D view of the connected paths show pathways and their direction of traffic flow. The flow originates from the source nodes and ends at a destination on Deck 4 Assembly Area (4Assem).

- Not all pathways are modelled highlighting a limitation; in the approach in MSC/1533, paths are chosen a priori. In the real case, there are more alternative connections/edges and routes that passengers can take.

- Nodes can have a forward and return path, allowing to some extent, counterflow. However, forward and backward loops increase the execution time and may send the solution into an endless loop.

The network view highlights in a clear manner, the critical paths. For example, if the edge between 2St2 and 3Corr2 is closed, then the passengers from deck 2 are stranded and can't proceed to Deck 3.

This network representation of escape routes is the basis of the evacuation analysis where passengers are located on nodes and need to proceed to the Assembly Area in the shortest amount of time. This is a linear problem and can be solved using the multi-commodity approach.

The approach is also suited to dynamic network reconfiguration being able to simulate an emergency which involves transient phenomena such as fire, smoke or structural damage resulting in changes to pathway access. The model can be dynamically updated to reflect the changed network in real time.

Design assessments using this technique can be used to audit existing designs for performance purposes; this is the “systems” view to evacuation.

5. SHIP MODELLING ASPECTS

The following simplifying assumptions are included:

- Passenger travel velocity is based on building data and adapted to fit within the context of this analysis.
- Passenger age, sex and skill levels have been averaged out for simplicity sake. The objective of this paper was not to better define travel metrics and parameters.
- Damage, smoke, heat and toxic conditions and ship sway effects have not been included in this model.
- Group behaviour is not considered.
- Ship motion and trim have not been considered.
- Capacity is defined as the number of passengers traversing an edge 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.
- Walking speed is in accordance to Table 3.4 of the MSC/1533 Circular. It is assumed that for all ages and sex, there is a mean value and a standard deviation. The final velocity for each egress traverse is calculated using the inverse of the normal cumulative distribution for a specified mean and standard deviation using a random probability.

MS Excel’s Solver macro is used to determine the edge traverse flow and optimises (maximum or minimum) the final egress duration value subject to ‘network flow constraints, i.e., to calculate the number of people traversing specific edges to minimise evacuation duration. The Excel Spreadsheet Solver is used being typical for these calculations. Note that the non-linear GRC solver was used due to the random input quantities.

Appendix 2 of MSC/1533 presents the IMO evacuation example. Simplified and advanced analysis methods are listed therein. Using these techniques, personnel traversing the paths had no options to use alternative paths; the Guidelines do not allow for alternatives to be assessed; the prime focus is on crowding but assumes all identified paths are available.

The Caledonia model for a night scenario case was created using the following techniques:

- the approach is theoretical and mathematical focussed to develop realistic ship evacuation simulations at a system level for the needs and requirement determination in a requirements and preliminary design environment.
- the methodologies are based on building evacuation studies.
- the example cited herein is based on a benchmark scenario and is not specific to cases and detailed configuration or environmental issues found during an actual evacuation. In this case, the primary evacuation case is the night case in accordance with the Fire Safety Systems Code (IMO, 2015) and includes the 95-passenger manifest.
- The routes are identified, and an evacuation duration is determined for each path; from source node to Assembly Area on Deck 4.
- The path which exhibits the longest evacuation duration is chosen as the representative duration for the evacuation, and
- 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). To express uncertainty in the crew movement solution, a Monte Carlo analysis is conducted to find the most likely evacuation time duration (>1000 iterations).

The Evacuation Model is made up of four functions/sub-models. They are, the Input Geometry model, the Node Plotting model (Node XL), the Path Optimisation Excel Solver model, the Hydraulic Analysis model and the Monte Carlo model.

The node plotter, NodeXL is a third-party tool that supports social network and content analysis (Socialmedia Research Foundation, 2020).

The model development process is as follows in Figure 5:

Input Geometry:

- Review deck plans to consider appropriate node locations.
- Define nodal and edge topography using a network representation.

- Define node properties, traverse length, area and entry/exit passage clear widths.

NodeXL

- Plot network to check topography layout and direction of flow. Some edges can be modelled as bi-directional.

- Set the maximum people density ranges from 0.54 to 3.8 persons/m^2; flow velocity is a function of people density.

- If the node is a stair, then an average value is used from the riser and tread data presented in Table 59.2 of the SFPE Handbook of Fire Protection Engineering (SFPE), (DiNenno, 2002)

Optimisation

- Define constraints to optimise (to minimise travel time); in this case, the edge capacity and the nodal flow balance criterion.

- Use Solver to determine the number of persons traversing each route (edge).

- Use NodeXL to check “trodden paths”.

Hydraulic Analysis

- Analyse nodes which are fed from more than one route using hydraulic technique.

- Check evacuation performance for the total number of persons is the sum of the maximum time for each edge that has been traversed. Maximum speed is defined as 1.19 m/s.

Monte Carlo model validation

- Using Monte Carlo technique, introduce a random variable parameter and determine the standard deviation of velocity data presented in Figure 59.4 of the Handbook of Fire Protection Engineering (DiNenno, 2002). 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 1000 times which each iteration displaying a different probability.

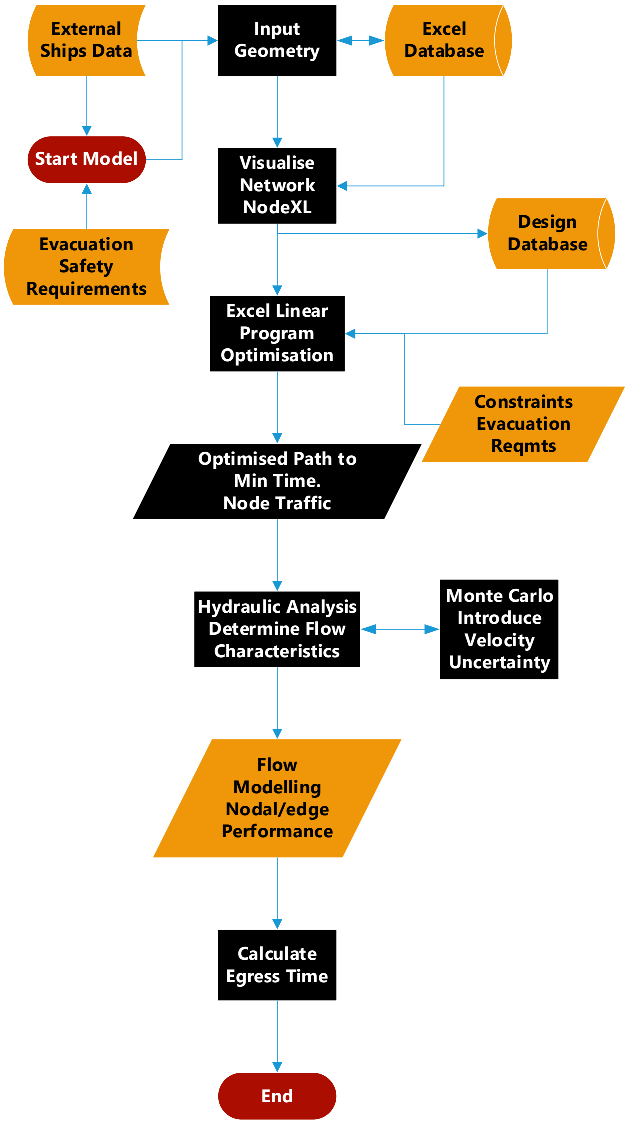

Figure 4. Simulation Sequence

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

Multi-Commodity (MC) network modelling was found to be a significantly better technique compared with traditional graph search algorithms. Moreover, it offers:

- The ability to include enhanced features that cover most of the SOLAS requirements presented in MSC 1533, and

- Demonstrated features that included multiple source and sink combinations, the advantage to add capacity/ and time constraints on edges and to consider the conservation of flow allowing identification of choke points.

This technique identifies 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 ameliorate existing designs.

To attend to the actual conditions during evacuation such as fire, smoke, visibility and ships motion, the MC network model can be adapted to represent individual passenger speed as required. This tool provides a means to resiliently and realistically model the evacuation parameters.

5.1. RESULTS - NIGHT CASE SOLUTIONS

Table 3 summarises the results from the Caledonia model:

Table 3. Case Descriptions and Results

Cases	*No Route Constraints – 95 passengers*	*Constraints Max 20 People/edge*	*Route closure – close down edge at Deck 3, Corridor 3 to 3 Corridor 2 due to fire conditions.*
Flow Balance Check	Yes	Yes	Yes
Constraints Check	Yes - 95 persons arrive at destination.	Yes - 95 persons arrive at destination.	Yes – Capacity unconstrained
Excel Answer Report Final Time (secs)	2004	3699	3976
Optimised Monte Carlo results	68% Result – 1901 to 2000 secs 20% Result – 2001 to 2100 secs.	74% Result – 3601-3700 secs 13% result – 3710 to 3800	68% Result – 3901-4000 secs 20% result – 4000 to 4100
Delay >30 secs	12	11	6
FOM if>1, does not meet performance standard	0.93	1.37	1.44
Comments	Fwd-back loop at final stage (3Corr2 to 3 Corr1) conduces endless iterations. Must be directed. See Figure 5.	The result indicates a complete redistribution of traversals causing longer delays times on alternate routes. See Figure 6.	The result indicates a complete redistribution of traversals causing longer delays times on some routes. See Figure 7.

See Chapter Model Verification and Validation (V&V) to check how the Monte Carlo technique supports V&V.

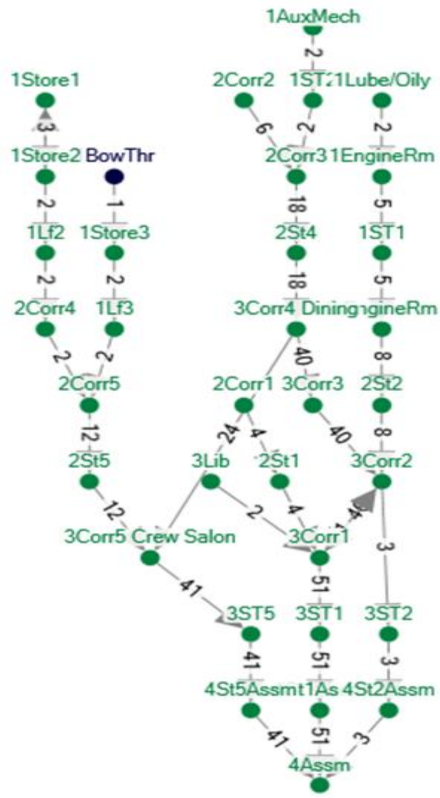

Figure 5. Case 1 Unconstrained People passage. Note high number of people in paths.

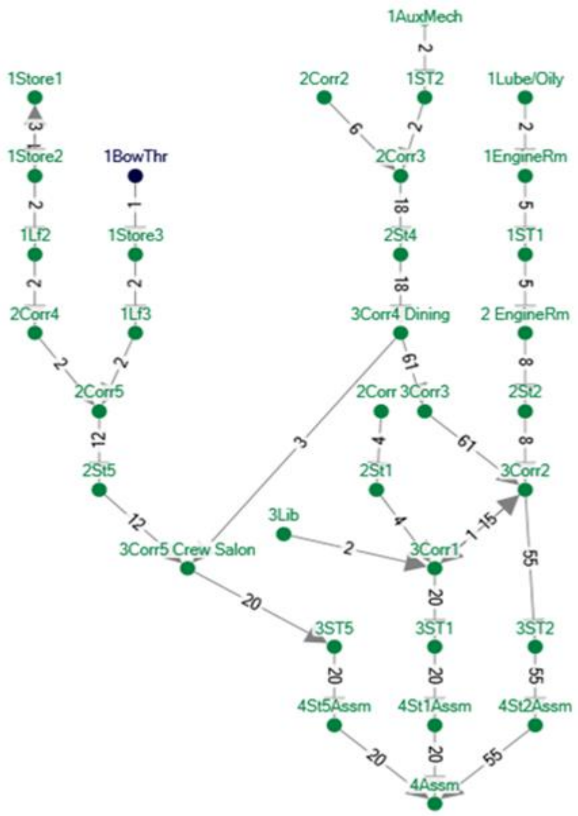

Figure 6. Case 2 People constraint to 20 maximum on selected paths

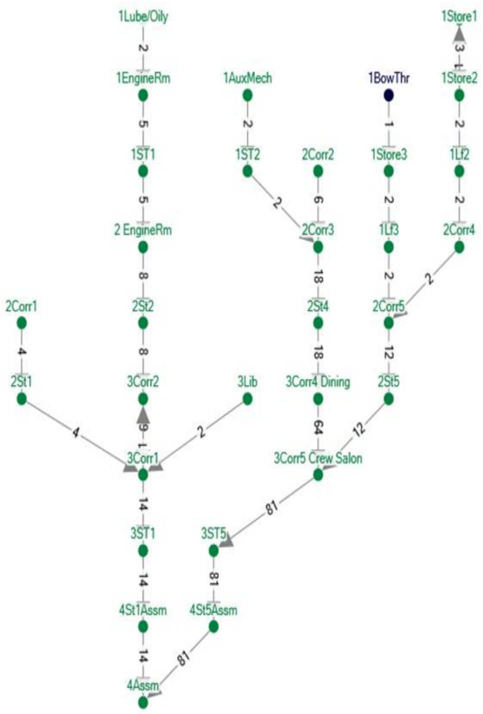

Figure 7. Case 3 Selected path closures at Muster Station.

6. DISCUSSION OF RESULTS

Three Case studies have been presented to show the Models use and the expected outcomes.

The results show:

- The evacuation problem can be represented by a network graph and can be described by an “Adjacency”” matrix which opens up the field to comparing networks by common descriptors, such as complexity.
- A network world view representation of the ship’s paths provides clarity and observance; evacuation topology is presented as a useful 2D map. Direction and the number of passengers traversing specific edges is clearly annotated.
- The ability to see clearly localised deficiencies in the evacuation capability.
- The development of egress time increases due to added constraints.
- Monte Carlo is a useful tool to identify the effect of uncertainty on the outcomes.
- A diminishing Figure of Merit representing a higher risk situation.
- The requirement to model sources and sinks to be carefully explored; the network should ideally be modelled as directed graphs. Any loop back links produces infinite loop characteristics.
- The network Model is flexible and allows changing the node and edge topography.

The simulation provides an efficient and resource optimised solution to evacuation. 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 (like smoke/fire, water, dark corridors, steam, oil/diesel, etc.) and aids such as visual and audio signs and alarms, announcements and PPE. 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 on attempting evacuation. As expected, evacuation time duration is not precise, as the uncertainty comes into play to determine likely evacuation durations.

7. MODEL VERIFICATION AND VALIDATION

The simulation is based on network analysis theory and linear programming. It uses a uses a well-established solver engine that has proven efficient and accurate in the calculation of linear simultaneous equations. Simulation time is related to the number of forward and back loops in the system.

The simulation modelled evacuation performance as outlined in the MSC 1533 guidelines. The guidelines included an example of a RO-RO ship which was modelled using this approach for the night time scenario. Similar results for the RO-RO ship proved this approach to be correct (Capizzi & Marian, 2019); these results were promising and initially provided a point of departure to extend the simulation to the case presented herein.

Shortest path problems were exercised with simpler models and found to provide accurate solutions (MIT, 2013). The approach using Excel Solver calculates the solution with two major constraints, the flow balance criterion and the boundary constraints. Both Solver criteria were met for the simulation cases presented in Table 1.

The network was modelled as an Adjacency Matrix, which was subjected to a Laplacian operation with the result that the network had real eigenvectors displaying connectivity properties, see Figures 8 and 9. 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 are connected t, i.e., its connections and importance of connections. In this case, as shown in Figure 8, Deck 2, Corridor 4 is the most influential vertex in the network. For design purposes, this area should be considered appropriately. This capability can be used to pin-point critical areas of node access; checking redundant safety paths and adequacy thereof. The same algorithm provides "Google" ranking of all the vertices.

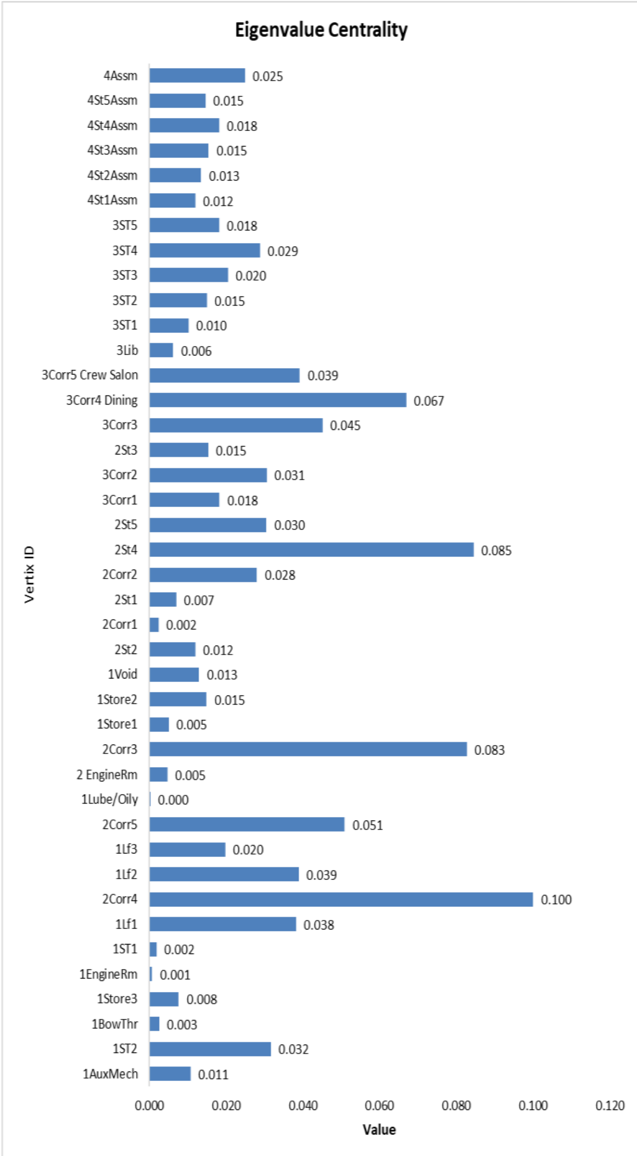

Figure 8. Eigenvalue Centrality

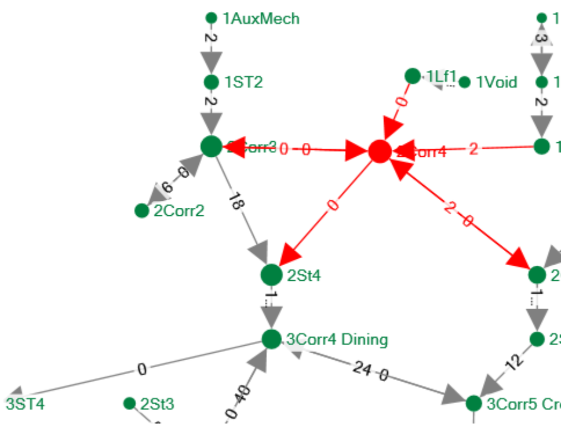

Figure 9. Deck 2 Corridor 4 sub-view showing inwards and outwards degrees in red.

With the network's properties and metrics, one would see the minimum vertex in and out degree of 2.

To include some degree of uncertainty in passenger movement speed as a function of path topology, passenger age and disability issues, the network was stochastically modelled to determine the standard deviation of available emergency data found in the building industry. This was subsequently used in a Monte Carlo solution using a random probability of occurrence for movement (velocity), thereby providing a best estimate based on the number of outcomes and realistic scenarios.

A typical evacuation case risk result is shown in Figure 10. This shows a Pareto analysis of the tabulated data (1000 iterations) for one of the Case runs. The orange line shows the accumulation statistic. 87% of the results were in the combined time buckets of 1901 to 2100 secs.

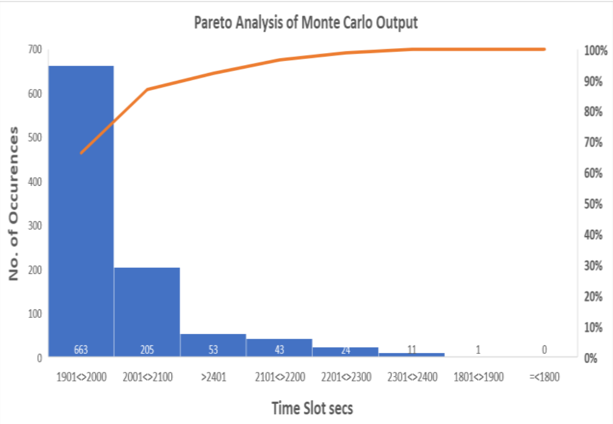

Figure 10. Pareto Analysis

8. CONCLUSIONS

The objective of this work was to find an approach to overcome the lack of simple, robust but accurate means to determine evacuation paths in a typical ship design. Simulation codes are nominally complex and requires significant over resources to develop simulations of evacuation scenarios.

MSC/1533 is limited in that one needs to pre-select paths, and for a complex layout, it is difficult to visualise the best paths with their inherent constraints. In addition, to forewarn passengers, the design of informational signage and how to represent "knowledge" of the ship to passengers can be understood with better visualisation. MSC/1533 is a written procedure too prescriptive and rather complicated to conduct by hand for simple layouts, let alone complex layouts. Presented as a mathematical model, it allows the user to change parameters, aspects and context, but most importantly, provides the opportunity to optimise route selection.

The research discussed in this paper investigated the feasibility to conduct 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 nodes and uses an iterative Excel Solver® numerical solution to solve the "shortest "path problem. Multi-commodity 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 advance to the state of evacuation analysis.

The Model provides both movement (time and path) and traffic congestion information on the selected shortest path. This is best utilised in both Systems feasibility studies for naval design purposes and/or validation analyses to characterise evacuation performance of existing ships using an expedient method of analysis.

The Model produced the desired expected outcomes; determination of the shortest path.

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

Each execution validates 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 very realistic representation of evacuation. This is an advanced means to tackle evacuation uncertainty.

A solution cannot be found if persons have no alternative path to reach the destination. Perhaps this is its greatest contribution and quickly identifies a potential safety issue.

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 can be used to configure person movements in real-time and can incorporate the implementation of latest and future means of assisting 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/compartments for a specific evacuation time. This underpins the strength of this approach.

9. RECOMMENDATIONS FOR FUTURE WORK

The research into this tool was not conducted to find replacement of specialist tools that have been developed over a long period of time. Rather, the aim of this research is to develop a robust Systems Engineering tool that can be used simply and efficiently to provide a system view of evacuation which is aligned to the standard practice and guidelines presented in MSC 1533. This has met its objective.

The research will naturally evolve the methodology to increase its level of realism even more by eliminating the simplifying assumptions in Section 5.

It is recommended that the tool be further developed to discover transient phenomena during enforced damage situations and to simulate the path dynamics to develop a time-based description of the damage scenario as it unfolds. Network metrics are to be explored for a means to rank networks in accordance to their degree of connection and their influence on connectivity. Other fire evacuation data can also be used to increase the knowledge of the case outcome. This is the real potential of this work.

10. ACKNOWLEDGEMENTS

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11. REFERENCES

1. ANDREWS, D. J. et al., 2008. *Integrating Personnel Movement Simulation into Preliminary Ship Design*. IJME, 150(Parts A1, A3).
2. BAIN, G., 2006. *Warship Recoverability Modelling.* Toulouse Frabce, QinetiQ SURVIVE software Series.
3. BELLAS, R. et al., 2020. *Analysis of Naval Ship Evacuation Using Stochastic Simulation Models and Experimental Data Sets*. Computer Modeling in Engineering & Sciences, pp. 1-25.
4. BEOM-JIN, P., DONGKON, L., HONGTAE, K. & JIN-HYOUNG, P., 2003. *The current status and future issues in human evacuation from ships*. Korea Research Institute of Ships and Ocean Engineering, Volume 41, pp. 861-876.
5. BONABEAU, E., 2002. *Agent-based modeling: Methods and techniques for*. Cambridge MA, PNAS, pp. 7280--7287.
6. BOONCHEV, D. & BUCK, G., 2005. Chapter 5 *Quantitative Measures of Network Complexity*. In: Complexity in Chemistry, Biology, and Ecology. Boston(MA): Springer, Boston, MA, pp. 191-235.
7. BOTEV, Z. & KROESE, D., 2014. *Why the Monte Carlo method is so important today*. Wiley Interdisciplinary Reviews: Computational Statistics, pp. 6:386-392.
8. BOULOUGOURIS, K. & PAPANIKOLAOU, A., 2002. *Modeling and Simulation of the Evacuation Process of Passenger Ships.* [Online] Available at: https://www.researchgate.net/publication/259976984 [Accessed 2020].
9. BROOKES BELL, 2020. *EVI - Evacuation Analysis Software.* [Online] Available at: http://www.brookesbell.com/service/software/evi-escape-evacuation-analysis [Accessed 2020].
10. CAPIZZI , V. & MARIAN, R., 2020. *Ship Evacuation and Systems Engineering.* Brisbane Australia, INCOSE/Systems Engineering Society of Australia.
11. CAPIZZI, V. & MARIAN, R., 2019. *Systems Graphing Algorithm Method for Ship Evacuation Studies,*. Sydney Australia, International Maritime Conference.
12. CASAROSA, L, 2008. *The integration of human factors, operability and personnel movement simulation into the preliminary design of ships. PhD,* University College London.
13. CHANG-WU, C., CHANG-ZUI, P. & HUA-AN, L., 2013. *Emergency evacuation route for the passenger ship*. Marine Science and Technology, 21(5), pp. 515-521.
14. CHEN, X. & ZHAN, F., 2006. *Agent-Based Modelling and Simulation of Urban Evacuation*: *Relative Effectiveness of Simultaneous and Staged Evacuation Strategies*. Operational Research Society, pp. 25-33.
15. COOK,, W., 2019. *Hisory of the TSP*. [Online] Available at: http://www.math.uwaterloo.ca/tsp/history/index.html#:~:text=The%20general%20form%20of%20the,and%20Merrill%20Flood%20at%20Princeton. [Accessed September 2019].
16. DINENNO, P. et. al., 2002. *SFPE Handbook of Fire Protection Engineering,*. Quincy MA, Society of Fire Protection Engineers.
17. DONGKON, L., HONGTAE, K., JIN-HYOUNG, P. & YOUNG-SOON, Y., 2004. Establishing the methodologies for human evacuation. *Computers & Industrial Engineering,* pp. 725-740.
18. EPSTEIN,, J., HAMMOND, R. & PANKAJAKSHAN, R., 2011. *Combining Computational Fluid Dynamics and Agent-Based Modeling: A New Approach to Evacuation Planning.* s.l., PLOS.
19. Excel Functions, 2020. *The Excel NORM.INV Function.* [Online] Available at: https://www.excelfunctions.net/excel-norm-inv-function.html [Accessed 2020].
20. Frontline Solvers, 2020. *Analytic Solver for Excel.* [Online] Available at: https://www.solver.com/analytic-solver-platform#tab3 [Accessed 2020].
21. FSEG, University of Greenwich, 2020. *maritimeEXODUS.* [Online] Available at: https://fseg.gre.ac.uk/leaflets/maritimeEXODUS_fseg_flyer_030912.pdf [Accessed 30 Dec 2020].
22. GAO, L., LANG, W., Liu, S. & Lo, S., 2014. *Passenger Ship Evacuation Simulation and Validation by Experimental Data Sets*. Procedia Engineering, 14(71), pp. 427-432.
23. GILLESPIE, J. W., 2012. *A dissertation submitted in partial fulfillment for the Degree of PHD.* Anne Arbor (Michigan): University of Michigan.
24. GWYNNE, S. & ROSENBAUM, E., 2016. *Employing the Hydraulic Model in Assessing Emergency Movement*. In: M. J. Hurley, ed. SFPE Handbook of Fire Protection. s.l.:Springer, pp. 2115 - 2151.
25. HAHSLER, M. & HORNIK, K., 2007. TSP – *Infrastructure for the Traveling Salesperson*. Journal of Statistical Software, 23(2), pp. 1-21.

26. HIFI, Y., 2017. *Probabilistic modelling of the process of evacuation for ship crises management.* University of Strathclyde (UK): ProQuest Dissertationbs Publishing.
27. IMO, 2015. International Code for Fire Safety Systems (Resolution MSC.98(73). 2015 Edition ed. s.l.:s.n.
28. IMO, 2016. *Revised Guidelines on Evacuation Analysis For New and Existing Existing Passenger Ships*. Maritime Safety Committee Circular, Issue MSC.1/Circ. 1533, p. 46.
29. International Maritime Organisation, 2020. *International Convention for the Safety of Life at Sea (SOLAS), 1974.* [Online] Available at: https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx#:~:text=Under%20the%20regulation%2C%20ships%20should,or%20loss%20of%20watertight%20integrity. [Accessed 2020].
30. KIM, H., LEE, D. & PARK,, J., 2003. *The status and Future Issues in Human Evacuation of Ships*. Safety Science, Issue 41, pp. 851-867.
31. MACAL, C. & NORTH, M., 2007. *Managing Business Complexity: Discovering Staregic Solutions with Agent Based Modeling.* New York US: Oxford University Press.
32. METER-KONIG, T., POVEL, D. & VALANTO, P., 2005. *Implementing Ship Motion in AENEAS — Model Development and First Results.* s.l., Springer, Berlin, Heidelberg, pp. 429-441.
33. MIT, 2013. *Applied Mathematical Technology.* [Online] Available at: http://web.mit.edu/15.053 [Accessed 2019].
34. RIGTERINK, D., PIKS, R. & SINGER, D., 2014. *The Use Of Network Theory to Model Disparate Ship Design Onformation*. International Journal of Naval Architesture Ocean Engineering, p. 484 to 495.
35. Socialmedia Research Foundation, 2020. *NodeXL.* [Online] Available at: https://www.smrfoundation.org/nodexl/ [Accessed 2020].
36. Society of Fire Protection Engineers, 2019. *SFPE Guide to Human Behaviour in Fire.* 2nd ed. Maryland USA: Springer.
37. SUGIYAMA, K., TAGAWA,, S. & MITSUHIKO,, T., 1981. *Methods for visual understanding of hierarchical system structures*. IEEE Transactions on Systems, Man, and Cybernetics, Volume SMC-11, pp. 109-125.
38. WRIGHT, S., 2016. *Optimisation.* [Online] Available at: https://www.britannica.com/science/optimization [Accessed 2020].

