Systems Graphing Algorithm Method for Ship Evacuation Studies

Vincent Capizzi

SYSTRA: vcapizzi@Systra.com

Dr. R Marian

UNISA: romeo.marian@unisa.edu.au

Prof. P Campbell

UNISA: peter.campbell@unisa.edu.au

1. ABSTRACT

This paper presents an outline of the development of a novel means to conduct evacuation modelling for maritime platforms using multi-commodity network theory and graph search techniques.

SOLAS/MSC.1/Circ.1533 (2016)[1] presents guidelines to conduct simplified/quasi-advanced analysis methods for the evacuation analysis of ships. The techniques presented by SOLAS are prescriptive and are limited such that path options with alternatives are difficult to analyse and don't consider uncertainty associated with dynamic and fluid evacuation environments, visibility, fire, smoke, ship motion and hazard propagation.

A linear programming model using multi-commodity networking and graphing algorithm techniques has been implemented in Excel. This model specifies crew and passenger numbers onboard ship, allows for personnel specifics and simulates ships geometry and path traversal difficulty. The simulation checks viable paths and determines the shortest route to the nearest safe point/muster station based on path difficulty and environmental conditions. Additional iterations in time allows for the hazard to propagate. Monte Carlo is used to pinpoint uncertainty. Updates to confidence levels determine the final probable shortest path/time.

---

[1] Revised Guidelines On Evacuation Analysis For New And Existing Passenger Ships, IMO - MSC.1/Circ.1533 6 June 2016

Initial findings indicate this Excel technique is feasible. As a systems engineering tool, it can be used in trade-off studies for ship layout purposes.

2. INTRODUCTION

The research into the development of an intelligent tool for evacuation from Naval ship platforms is based on the premise that it is analogous to the puzzle presented by the Traveling Salesman Problem (TSP). A salesman must travel between several cities (nodes). The order in which he does this is not important as long as he visits each once during his trip and finishes where he started. Each city is connected to other close cities by links (designated as edges) by airplanes, or by road or railway. Each of those links between the cities has one or more weights (or the cost) attached. The cost describes how "difficult" it is to traverse this edge on the graph, perhaps by the length of the edge, or the time required to complete the traversal or its individual cost. The salesman wants to keep both the travel costs and the distance he travels as low as possible. This problem, used in operations research, focuses on optimization; to seek a better solution being cheaper, shorter, or faster. An algorithmic model is developed to solve the TSP and is based on nodes and edges exhibiting a network like structure typically referred to as a Graph algorithm. The Traveling Salesman Problem is one of the most intensively studied problems in computational mathematics and has been in existence since the 1800s by the Irish mathematician Sir William Rowan Hamilton and by the British mathematician Thomas Penyngton Kirkman[2].

When the Graph algorithm is applied to ship platforms, the following similar traits are identified:

a) The ship layout can be represented as a TSP with constraints identified and "difficulties" along links modelled;
b) The ship is represented by a routing network using nodes describing originating and transition points (compartments, rooms) and edges (links – corridors, passageways, stairs) connecting the nodes; and
c) Adopting an optimisation algorithm such as that provided by a technique known as the multi-commodity flow allows for some certain degradation with time and allows for optimising routes taken by the crew in an emergency. There is a notable difference with the TSP: the start and the end of the travel are different and set for each room.

This paper covers the above points, the constraints for both the platform and using the Multi-commodity flow algorithms, as well as their advantages.

Note that there is a plethora of evacuation models on the market[3]; the development of this application is seen as an alternate view to the standard approaches available.

---

[2] History of the TSP; http://www.math.uwaterloo.ca/tsp/history/index.html

[3] The current status and future issues in human evacuation from ships, D Lee, H Kim, JH Park, BJ Park, Safety Science 41 (2003) 861–876.

3. BACKGROUND

In response to major ship disasters, Nation States have moved towards internationalization of laws to be introduced that utilise local regulations, agreements or understandings among the leading maritime nations. 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 Safety Of Life At Sea (SOLAS) guidelines. As part of the IMO's "raison d'être", emergency evacuation simulation now plays an important part in the consideration of design of vehicles, ships, aircraft or buildings with interest coming from academic, industrial and scientific fields[4].

The implementation of SOLAS Regulation II-2/28-1.3, called for an appointed Sub-Committee on Fire Protection (FP) to develop guidelines for evacuation analysis for passenger ships and high-speed passenger craft. This promulgated a series of circulars, the most important being MSC/Circ.1033 (2002) & MSC.1/Circ.1238 (2007) which provide guidelines for the evacuation analysis for ship platforms. Currently MSC/1533 (2016)[5] replaces the previous two circulars and provides similar guidelines. To make correlation uniform, benchmark scenarios and relevant data are specified which are used to determine the evacuation performance of the ship. Most data and parameters stated in the guidelines are based on well-documented data coming from civil building experience. These guidelines provide performance criteria in terms of total calculated evacuation time compared to the allowable evacuation time.

4. EVACUATION EXAMPLE FROM MSC/1533

The MSC/1533 for ship evacuation provides:

1. the use of guidelines when conducting evacuation analyses, early in the design process, on new passenger ships to mitigate the risks of safe evacuation and put in place structural and procedural practices to deliver a safe ship; and
2. the encouragement to conduct evacuation analyses on existing passenger ships using these guidelines to uncover inherent evacuation difficulties in order to effect a perceived improvement to evacuation performance; to identify congestion points and/or critical areas and to provide recommendations as to where these points and critical areas are located onboard[6].

MCS/1533 provides an example of the use of the guidelines; the example refers to an early design analysis of arrangements of a hypothetical new cruise ship. The performance standard is assumed to be 60 mins, as for ro-ro passenger ships. It was noted that, at the time this

---

[4] DiNenno, P.E. et al. The SFPE Handbook of Fire Protection Engineering, 3rd Ed., 2002.

[5] Revised Guidelines On Evacuation Analysis For New And Existing Passenger Ships, IMO - MSC.1/Circ.1533 6 June 2016

[6] MSC 1533 states "it is the company's responsibility to ensure passenger and crew safety by means of operational measures, if the result of an analysis, conducted on an existing passenger ship shows that the maximum allowable evacuation duration has been exceeded, then the company should ensure that suitable operational measures (e.g. updates of the onboard emergency procedures, improved signage, emergency preparedness of the crew, etc.) are implemented"

example was developed, no such requirement is applicable for passenger ships other than ro-ro passenger ships.

The example ship exhibits seven decks (Deck 5 to 11); Deck 8 is the muster station. Corridors are connected to stairs that allow passages through to Deck 8. The lower decks are Decks 5,6 and 7. The upper decks are 9, 10 and 11. A diagrammatic view is shown in MSC/1533 and is presented in Figure 1 as a “hydraulic diagram”.

The corridors connect to doors, stairs or openings; the goal to reach the Muster Station on Deck 8. 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 449 passengers/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.

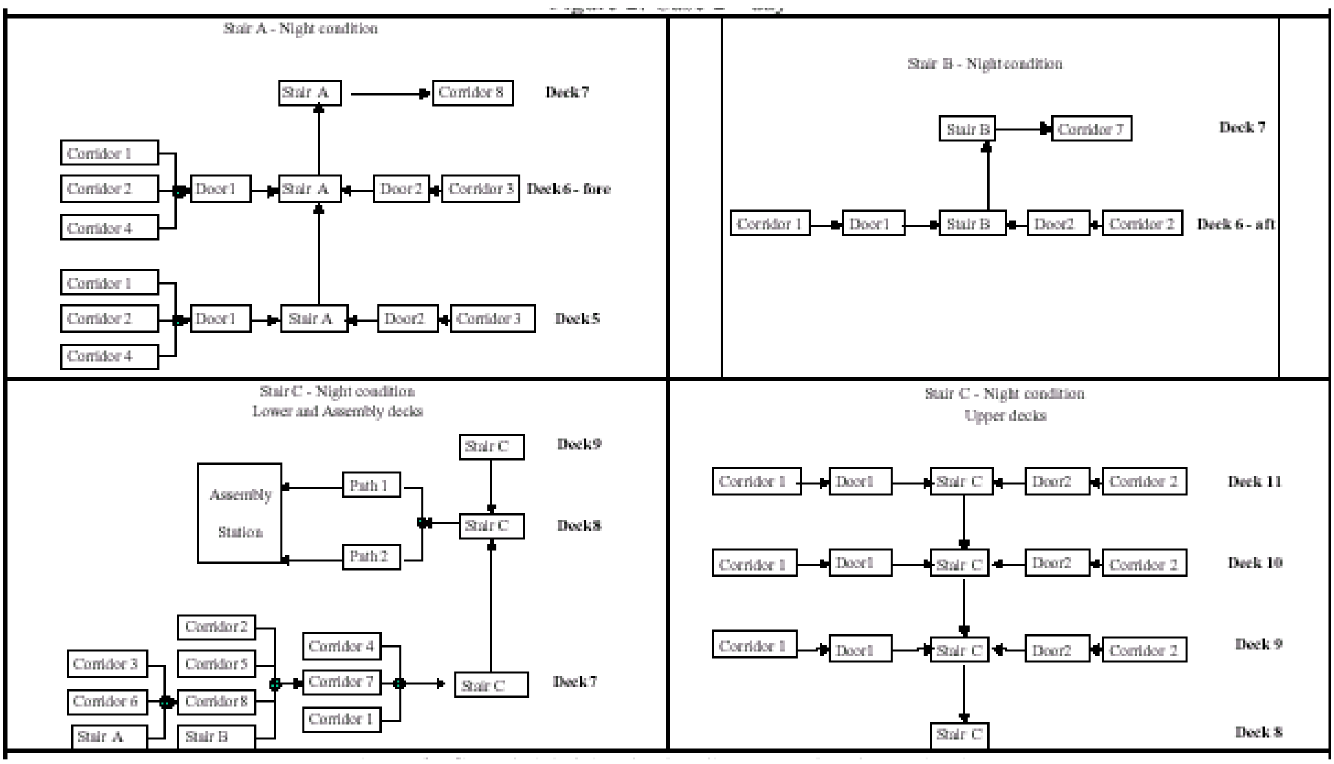

Figure 1 From MSC/1533 – Case 1 Night Case Hydraulic Representation

The MSC/1533 evacuation performance standard is defined as:

1.25 (R+T) + 2/3 (E+L) ≤ = n[7]; where “n” for passenger ships = 60 mins.

[7] Ibid 4

E+L is the embarkation and launching time = 30 mins.

R is response duration – for purposes of indicating a benchmark, R should be 10 mins for the night time scenarios and 5 mins for the day time scenarios.

T is the total travel time, calculated.

The example considers the overall ships geometry plus the factors and assumptions; the total evacuation time is calculated to be 41 minutes and 38 seconds; this meets the performance standard for the night; Case 1.

The focus is therefore the calculation of "T"; the other parameters are based on history/experience. The final calculation of "T" is stated as 437.5 seconds, that being the longest duration across the escape routes.

5. NETWORK VIEW

To display a 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

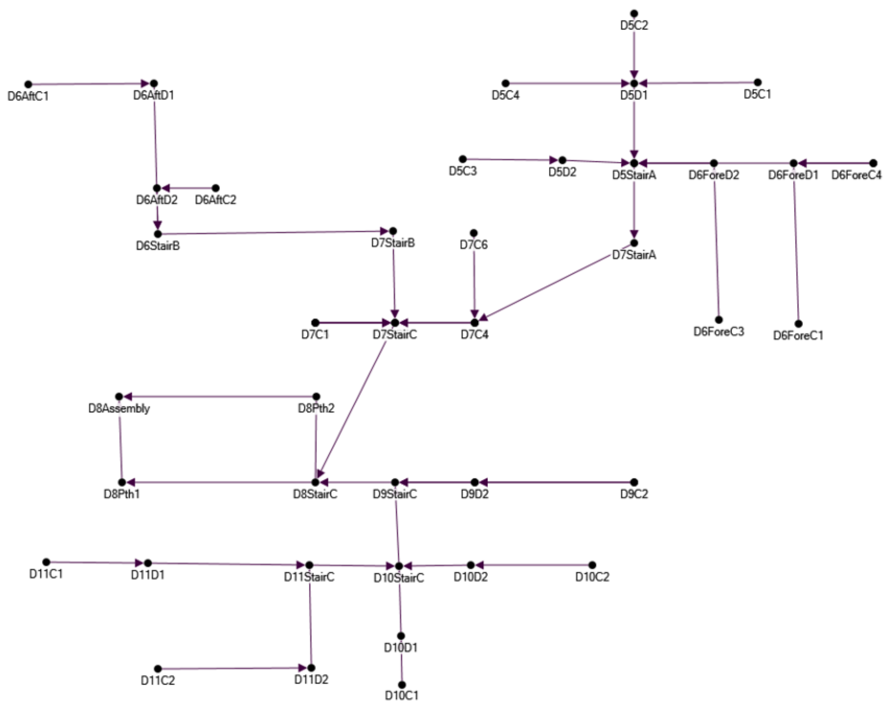

Figure 2 below.

The label refers to the location onboard ship:

> “D”x refers to Deck x; “C”y refers to Corridor y; “D” In the body of label refers to Door. For example, D12D3 refers to Deck 12 and Door 3 the second ‘’D’’ refers to Door).

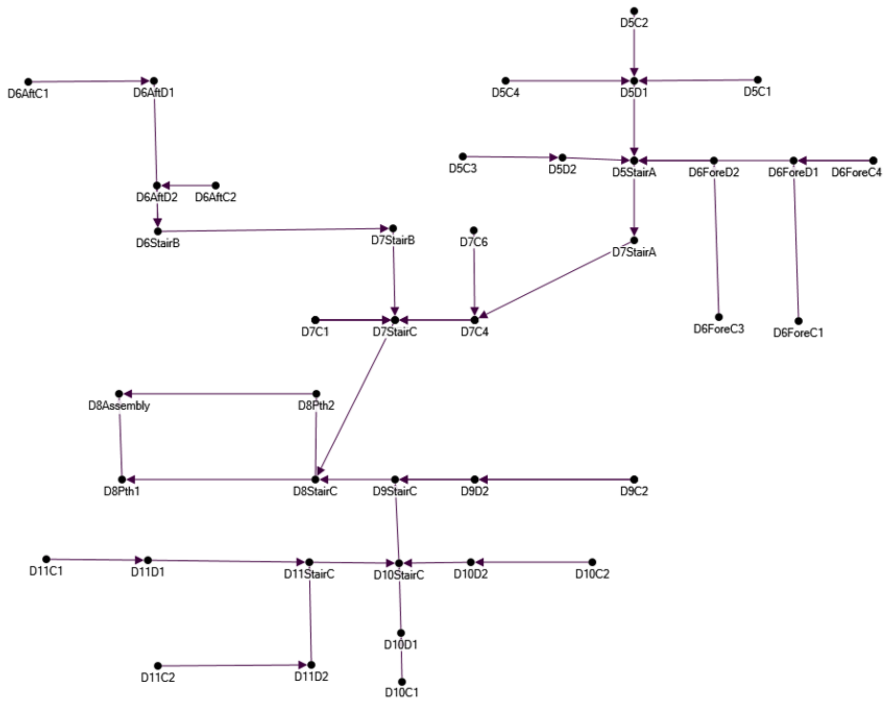

Figure 2 Edge-Nodes Representation.

The following observations are made:

a) A 2D view of the connected paths show pathways and their direction of traffic flow. In this case, flow originates from the source nodes and ends at a final destination on Deck 8 Assembly Area (D8Assembly). The 2D view also makes it easier to identify 3D aspects of location; and

b) For this example, not all pathways are modelled highlighting a limitation of MSC 1533, that is the paths are chosen a priori. In the real case, there are more connections/links and routes that passengers can take.

The network view also highlights in a clear manner the critical paths. For example, if Stair C between Deck 8 and 9 is closed, then the passengers from decks 9 to 11 are stranded and can't proceed to Deck 8 Assembly Area.

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

The approach is suited to dynamic network reconfiguration; 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.

This benefits design studies and can be used to audit existing designs for performance purposes; this is the "systems" view to evacuation and provides the basis of this research.

6. Multi-Commodity Modelling[8]

Multi-commodity flow modelling 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 shipping links. 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 an Assembly Area just prior to evacuation. 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. It is also known that routes have capacity restrictions. The objective is to minimise the travel time (Cost) and ensure all passengers reach their destination.

The modelling is characterised by:

a) flow capacity along edges and secondly, cost is assigned for each edge, i.e. the time duration to travel along edge;

[8] Applied Mathematical Programming, Bradley, Hax, and Magnanti (Addison-Wesley, 1977)

b) edge capacity, the sum of flows across an edge does not exceed its capacity requirements;
c) flow conservation at the source and sinks, i.e. Inflow demand equals outflow supply; and
d) 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 cost or capacity. Therefore, for a minimum – time flow problem with n nodes:

xi j = Number of passengers traversing from nodes i to j using edge *i– j*[9]

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

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

There are numerous publications in the field; multi-commodity modelling is a universal approach that can also be adaptable to many industrial problems[10].

The following observations are made:

a) Network models are special structures in linear programming, making them efficient and effective;
b) The approach presented is simply derived from specializing the rules of the simplex method to take advantage of the structure of network models;
c) The algorithms are extremely efficient and can permit 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
d) This technique can be easily modelled and implemented using MS Excel with the Solver add-on.

7. The Ship Model

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 systems view.

Appendix 2 of MSC 1533 presents the IMO evacuation example[11]. 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.

[9] ibid 3
[10] Reference Applied Mathematics Programming, Chapter 8, Subparagraph 8.8 Reference MIT website; http://web.mit.edu/15.053/www/AMP-Chapter-08.pdf.
[11] Ibid 4

The Ro-Ro[12] ship representation of the model shown in Figure 1 for a night scenario case was created using the following techniques:

a) 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 design environment;
b) the methodologies are based on building evacuation studies;
c) the example cited herein is based on a benchmark scenario and is not specific to particular 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 FSS Code13 and includes a passenger manifest;
d) The prime aim of the exercise is to determine the egress duration for passengers, and to identify congestion points. If these points exist, then the design iteration is required to mitigate these points as they impact dramatically egress duration;
e) The approach in this example is similar to that found in MSC 1533 with respect to process and conventions; and
f) The assumptions included:
    i) Passenger travel velocity is based on building data and adapted to fit within the context of this analysis;
    ii) 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;
    iii) Damage, smoke, heat and toxic conditions and effects have not been included;
    iv) Group behaviour is not considered;
    v) Ship motion and trim have not been considered;
    vi) 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;
    vii) Walking speed is in accordance to Table 3.4 of the MSC 1533 Circular[14]. 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;
    viii) MS Excels Solver macro is used to determine the edge traverse flow and optimise (maximum or minimum) the final egress duration value subject to 'network flow constraints', i.e. calculate the number of people traversing specific edges to minimise egress duration. Figure 3 below presents the spreadsheet used in the calculations and a view of the Solver input parameters. Note that the non-linear GRC solver was used due to the random input quantities;

[12] Ro-Ro – Roll on, roll off.
[13] FSS Code - International Code for Fire Safety Systems (FSS Code) (resolution MSC.98(73))
[14] Ibid 4

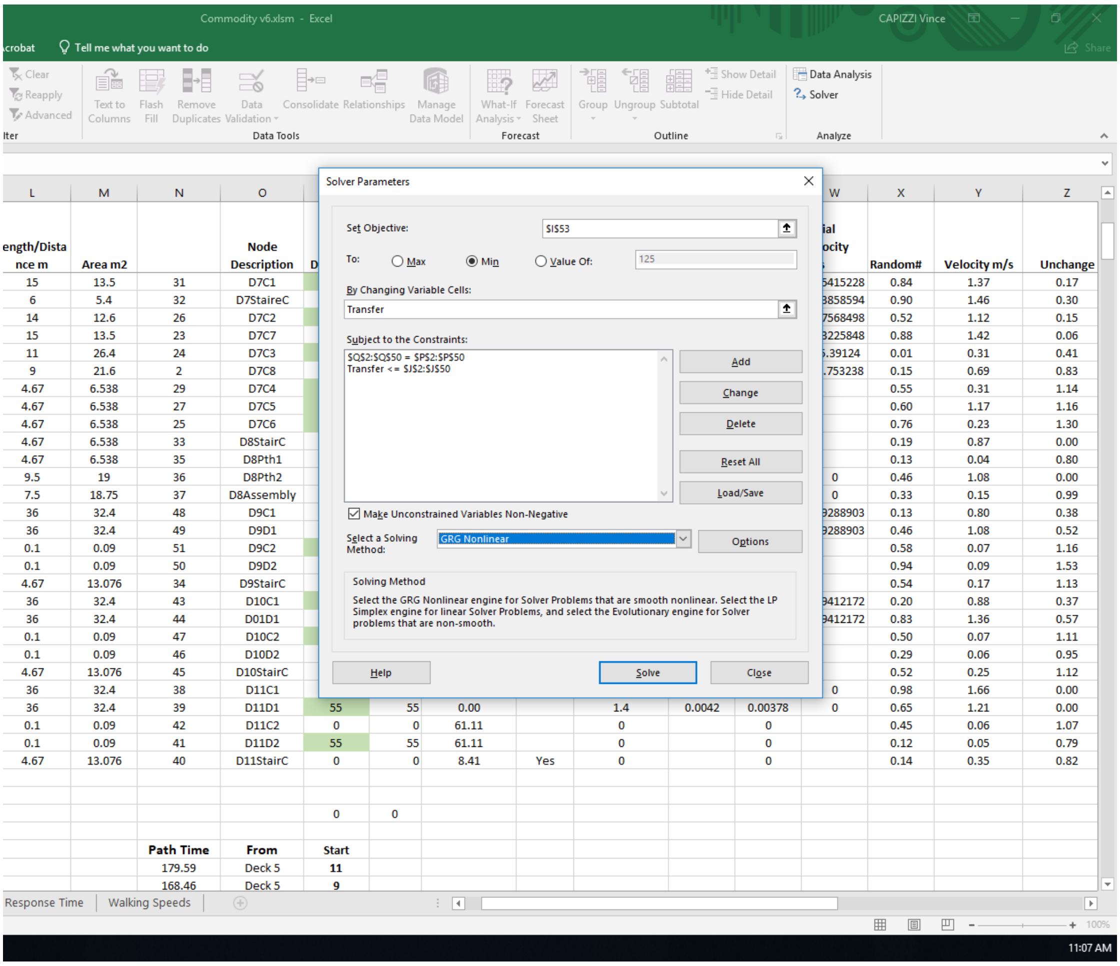

Figure 3 Excel Spreadsheet Solver View

ix) The routes are identified and an egress duration is determined for each path; from source to Assemble Area;

x) The path which exhibits the longest egress duration is chosen as the representative duration for the evacuation; and

xi) To express uncertainty in the solution, a Monte Carlo analysis is conducted to find the most likely time duration delivered (>500 iterations).

The model process is as follows:

i) Define nodes and edges using a hydraulic representation;

ii) Define edge properties, length, area and passage clear width;

iii) Define constraints to optimise (minimise travel duration); and

iv) Use Solver to determine the number of persons traversing each passage;

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

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

a) The ability to include enhanced features that cover most of the SOLAS requirements presented in MSC 1533; and
b) 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.

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 passengers as required. This tool provides a resilient and realistic model of evacuation parameters.

7.1. Case 1 Result - Night Case Solution with no Capacity Restriction

In this solution, it is assumed that Capacity of flow is not a restriction, but however it highlights congestion areas.

The MSC1533 calculated result is 437.5 seconds. Table 1 presents results for this same case using MC modelling.

Egress duration sec	Number of Hits, Monte Carlo Analysis
Below 350 seconds	113
Between 350 and 450 seconds	369
Greater than 450 seconds	70

Table 1 Night Case Solution with no Capacity Restriction

The results indicate that the most likely result is between 350 and 450 seconds which aligns with the MSC 1533 result of 437.5 seconds.

Congestion was identified as identified in Table 2; generally, in accordance with MSC1533.

DECK	Location From	To
5	D5StairA	D6StairA
6	D6StairA	D7StairA
6	D6StairB	D7StairB
7	D7C7	D7StairC
7	D7C8	D7C7
7	D7StairA	D7C8
7	D7StairB	D7C7
7	D7StairC	D8StairC
8	D8StairC	D8Pth1
8	D8StairC	D8Pth2

8	D8Pth1	D8Assembly
8	D8Pth2	D8Assembly
9	D9StairC	D8StairC
10	D10StairC	D9StairC
11	D11StairC	D10StairC

Table 2 Congestion Areas

7.2. Case 2 Result - Night Case Solution with Capacity Restriction

The model was calculated using the Capacity restriction along the edge paths. The final transfer of persons to the Assembly Area from Path 1 and Path 2 was 208 and 241 respectively totalling 449 passengers with a total duration of 414 seconds.

To highlight egress difficulties due to structural damage and/or fire or smoke impediments, a 50-person Capacity restriction was applied to Path 1. Additionally, as a second capability example, Path 1 was completely shut off. The results of this analysis are shown in Table 3 below:

Capacity Restriction	Persons traversing Path 1	Egress Duration Impact Seconds
None	213	410
50 persons	50	444
Shut down – cannot traverse	0	557

Table 3 Night Case Solution with Capacity Restriction

The above result reflects the diminishing capacity of Path 1 to egress optimally with restrictions in place.

8. Conclusions

The following conclusions have been reached from this research:

a) Evacuation paths can be modelled that use cost functions that account for time, difficulty of cross compartment movement difficulty to move from compartment-to-compartment, additional 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 egress. But the egress time duration is not precise, as the probability comes into play to determine likely egress durations;

b) Multi-commodity graph modelling is an appropriate technique to calculate evacuation systems. It is suited to evacuation optimisation incorporating user friendly interactive communication with ships system configuration;

c) The tool is flexible and adept to conducting initial systems engineering needs, requirements and conceptual studies of ship evacuation systems. Various evacuation restrictions concerning fire, some toxic gas and structural damage can be played out quickly and efficiently by changing path capacity and managing velocity outcomes;

d) A solution cannot be found if persons have no alternative path to reach the destination. Perhaps this is its greatest contribution; and

e) With the capability to configure paths (edges), it can dynamically assess damage or fire fronts by incorporating environmental transients which can be used to configure person movements in real-time.

9. Recommendations

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 tool that can be used simply and efficiently to provide a system view of evacuation and is aligned to the guidelines presented in MSC 1533.

It is recommended that the tool be further developed to cover transient phenomena during damage forced situations and to simulate the path dynamics to develop a time-based description of the damage scenario as it develops. This is the real potential of this work.