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How to Guide Emergency Evacuations on Cruise Ships?

Modelling with Optimization and Simulation Methodology

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Contents

Abstract

In recent years, the number of cruising tourists has been growing rapidly, but some serious cruise ship accidents have also aroused safety concerns of the public on travelling with cruise ships. However, the fixed emergency evacuation routes that are suggested in a boarding drill or pasted behind a cabin door is inapplicable in a real emergency because of ignoring the uncertain influence of the hazards. The existing research about emergency evacuation on vessels is rare, and how to guide the evacuees under emergency situations is also seldom mentioned. Moreover, modelling the evacuation on ships also needs to consider unique features of ships, such as unstable conditions during emergencies, including shaking, heeling and sinking, and the confined steel environment on ships, where internal data communication is totally dependent on cables.

In this thesis, an implementable evacuation guiding model is proposed. In the proposed model, differentiated evacuation routes are suggested to evacuees with consideration of different movability and walking speed of them. In addition, the guiding of evacuees is also realizable in the proposed model, with the cutting-edge sensor mesh technology developed by ScanReach, with which the wireless data transfer in confined steel environments is feasible. The proposed model is simulated in a framework of rolling horizon, updating the dynamics of an emergency evacuation by continuously gaining the latest information of hazard situation and evacuees movements.

Keywords: evacuation, guide, cruise, vessel, ship, fire, hazard, uncertainty, rolling horizon.

1. Introduction

In recent years, the number of cruise passengers is steadily growing and expected to reach 30 million in the year of 2019, increasing by around 69% over the last decade (CLIA, 2019). However, as cruising is becoming a more and more popular choice for tourists, several serious cruise accidents have also aroused much attention of the public. For instance, in 2012, the Costa Concordia cruise vessel sank after running aground near Tuscany, resulted in 32 death and numerous injuries. In 2014, the Sewol ferry sinking accident robbed 296 lives, caused 142 injuries and 8 missing. According to Maritime Injury Guide (2018), from 2005, 448 significant cruise vessel accidents were reported, and fire is one of the most common cruising safety concerns, with 79 fire reports on cruise vessels between 1990 and 2011. For these reasons, it is essential to make sure that cruise passengers can quickly and safely evacuate during emergencies.

In this thesis, a fire on board is denoted as the typical type of hazard. The remainder of this thesis is organized as the following flow. In Section 2, relevant regulations and standards about emergency evacuations on maritime ships are reviewed. In Section 3 provides a review of literature on evacuation related research and models, and a short summary and possible future development are proposed. Section 4 introduces the methodology used in this thesis, to model and guide the emergency evacuation on cruise vessels, and the technical premise and support is also stated in this section. In Section 5, an evacuation model is proposed, with the criteria to select evacuation routes. The proposed model is implemented into simulation in Section 6, with three main findings and based on which, the original model is updated twice. Section 7 is the discussion section with limitations of this thesis, and also suggestions for future research. In Section 8 is the conclusion.

2. Relevant Regulations

The International Maritime Organization (IMO), is an agency administrated by the United Nations, whose role is to build a framework for the regulations of a fair and efficient shipping industry, including shipping safety and marine environment protection (IMO, 2013). Most of IMO's work is distributed to a number of committees, and one of which is the Marine Safety Committee (MSC), who is responsible for issues related to shipping safety (IMO, 2013).

IMO MSC.1/Circ.1533 (IMO, 2016) provides the latest revision of the guidelines on evacuation analysis for both new and existing passenger ships. The guidelines specify six benchmark scenario cases to be considered in evaluation, assessing the performance of ships. Two distinct methods are proposed in the guidelines, a simplified evacuation analysis approach and an advanced one. The simplified evacuation analysis approach is based on a series of assumptions that simplify the real situations, for example, all the passengers and crew begin evacuation at the same time and do not hinder each other. However, the advanced one is a computer-based simulation approach, which characterizes each individual, ship layout details and interaction between the individuals and the ship layout. Due to the obvious limitations of simplified evacuation analysis approach and increasing complexity of conditions on board in emergencies, IMO suggests that the use of the advanced approach is preferred. With the advanced evacuation analysis approach based on computer simulation, the duration of the evacuation is calculated and possible congestion points are identified. The aim of the guidelines is to recommend interested parties to conduct the analysis early in the design stage on new passenger ships and also on existing ships, expecting to help improve the ship design and enhance safety by detecting inadequate evacuation arrangements and congestion points.

In the guidelines, detailed discussion about the methods of evaluation, scenarios to be considered and performance standards are presented. The specific steps of evaluation is involved in the section of evaluation methods in the guidelines. In the scenarios section in the guidelines, the drawings of decks and the distribution of population demographics are presented. Some fixed instructions of evacuation are also given in this section. The performance standards section in the guidelines mainly includes the definition and calculation methods of the standard indicators, such as flow of persons, flow durations and travel durations. The data of the response time of evacuees in day and night scenarios are provided. The data of moving speed and maximum flow in terms of crowd density is also available in this section, and will be used in the modelling part of this thesis. In addition, the guidelines also involves some examples of evaluation, and can be referred to.

However, even if the approach is sufficient to deal with simulation evacuation from mathematical and theoretical points of view, IMO still shows concern about whether the verified data is sufficient in practical application to real emergency cases. The reasons for such concern are followed. First of all, the specified data and parameters in each scenario are based on well-documented data from civil building experience. Although buildings shares some features with passenger ships but there are still some differences between them. Hence, the data from buildings is not entirely reliable to be implemented to a simulation on ships. In addition, the acceptable evacuation durations in the guidelines are typically stipulated for fire disasters, and are not necessarily applicable for other kinds of disasters. Moreover, with many assumptions listed in the guidelines, the hazardous situation is actually simplified. For instance, smoke, heat and toxic fire products are not considered, and the impact of ship motion, heel and trim are also ignored. Unexpected individual behaviours are also ruled out according to the assumptions, such as the non-consideration of family group performance.

Generally, IMO suggested an evaluation analysis approach for the evacuation performance of passenger ships through computer simulation based on benchmark scenarios, hoping to improve ship design and enhance safety, but with concern over the applicability in real hazardous situations. But the IMO guidelines does not impose fixed rules or regulations on evacuations that take place on vessels, and it mainly suggest evaluation methodologies of the evacuations on vessels, and provides some benchmark scenarios for simulation and the necessary data and definitions for reference.

3. Literature Review

This section presents a review of literature regarding emergency evacuation planning and management. There are mainly three categories of research in this topic, firstly is the pre-disaster evacuation planning, for example, drills. The second category focuses on models that determine the optimal evacuation route, usually through optimization methods. The third category emphasize the evaluation of evacuations, and is typically based on simulation models. This thesis is supposed to work out an model that guides the evacuees on cruise vessels with determined optimal route during a fire disaster, and also implement the proposed model into simulation, evaluating the performance of this model. However, pre-disaster evacuation planning is mainly fixed, and is not related to the proposed model in this thesis. Therefore, the review will emphasize the studies which are based on optimization and simulation methodologies and valuable for reference. In addition, a discussion of uncertainty in evacuations is also included in the review section, because the proposed model in this thesis is supposed to handle the uncertainty during evacuations.

Furthermore, because this thesis is about guiding emergency evacuations that take place on cruise vessels, the review will also involve evacuation related research about cruise vessels. However, such kind of articles are relatively rare. In addition, Casareale et al. (2017) confirmed the similarity between evacuations take place in buildings and on ships, by doing simulations. For this reason, the studies about evacuation that take place in buildings and other constructions with similar layouts, such as a stadium, are also going to be reviewed in this section.

With respect to the means of traffic during evacuation, Aalami & Kattan (2018) stated that there are usually three types of evacuation, vehicular, transit and pedestrian. Because this thesis is about guiding evacuation for passengers on cruise vessels, where the main traffic is pedestrians, the review will include research of pedestrian evacuations rather than those with vehicles.

3.1. Research on Evacuation Models

3.1.1. Basic Concepts and Principles

Firstly, several basic and fundamental principles in terms of evacuation modelling are reviewed. According to Bayram (2016), approaches to assign traffic is the basis for evacuation models. In the research of traffic assignment , the user equilibrium (UE) and system optimal (SO) principles proposed by Wardrop (1952) are widely used. UE is the first principle defined by Wardrop, and the definition is that, when the travel time of all used routes is shorter than that would be taken on any unused route, the user equilibrium is achieved. But UE approach is almost unrealistic to apply in real situations as this approach assumes that the evacuees have all relevant information about traffic network and can judge the optimal routes (Bayram, 2016). The SO principle is the second principle defined by Wardrop, where the average travel time of all evacuees in the system is minimized. Bayram (2016) stated that usually evacuation traffic authorities are aimed to minimize the total evacuation time, that is, achieving a system optimum (SO). In existing studies about traffic assignment models, the nearest allocation (NA) approach is commonly used with aim of planning the traffic. In the NA model, each evacuee uses the shortest path to reach the nearest shelter. However, Bayram (2016) argued that, NA approach may cause poor system efficiency as evacuees tend to behave selfishly and only concern their own interests. In addition, the constrained system optimal (CSO) approach is a product of the trade-off between SO and NA/UE approaches (Bayram, 2016). CSO was firstly introduced by Jahn et al. (2005) , which includes individual preferences as side constraints on the base of SO approach, thus achieving both fairness and system efficiency at the same time.

Zhang & Chang (2014) introduced a dynamic evacuation model according to the SO principle, and applied to urban emergency situations with mixed flows of vehicles and pedestrians. Zhang et al. (2018) proposed an algorithm based on UE principle and K shortest paths algorithm, to model emergency evacuations. Duan et al. (2016) calculated the optimal evacuation route in campus during emergencies according to the Wardrop equilibrium model, implementing both UE and SO principles, and the performance of the two principles are close to each other in the typical case.

3.1.2. Objectives of Evacuation Models

Optimization is a widely used methodology to determine the optimal evacuation route in the articles about evacuation modelling. In an optimization-based evacuation model, it is necessary to have a comprehensive review of different objective functions implemented, because the choice of criteria to identify the optimal route is crucial, when modelling evacuations.

The most commonly used criteria in the objective function of evacuation models include network clearance time, total or average evacuation time, total or average length of evacuation route, social welfare, total cost, casualty and number of evacuees that reach safety. Indeed, some of the criteria used in objective functions are supported by the fundamental principles in evacuation problems that stated in previous contents. For instance, network clearance time is corresponding to the SO principle, and length of evacuation route is corresponding to the UE principle. According to the type of disaster and the aim of the evacuation responsible authorities, various objectives can be employed for evacuations (Han et al., 2007). Wang et al. (2016) introduced an evacuation model that can switch the objective function according to different emergency situations and satisfy the preferences of different decision-makers.

However, because it is common to have more than one criterion to determine the optimal solution in evacuation models, in many papers, a multi-criteria objective function is adopted. Yu (1975) introduced two classical approaches to construct multi-criteria objective functions, denoted as one-dimensional and lexicographic ordering. In one-dimensional approaches, a real-value utility function is constructed and maximized, by assigning different weights to all the criteria. However, with a lexicographic approach, the criteria are ordered at the beginning. The first-ordered one is firstly maximized, and with the first one fixed, the second criterion is then maximized, and so on. According to Sherali & Soyster (1983), with a one-dimensional approach, the set of weights are decided subjectively according to the importance of each criterion. Similarly, with lexicographic approach, Sherali & Soyster (1983) believed that it is unrealistic to pre-determine the weight of each criterion, but one can assume that the incremental improvements of the top-ordered criteria can have more value than those of lower-ordered ones. Sherali (1982) also introduced the characterizations and computations of weights assigned to lexicographic ordered criteria in the models with multi-criteria objective functions.

In the research about evacuation on vessels, for instance, if a cruise vessel is on fire, ideally the optimal evacuation route should be of the shortest length and takes least time for evacuees to get out and with least casualty. But in reality, the optimal evacuation route may not be the one shortest in physical length, considering the influence of different factors, such as toxic gas produced by the fire, potential congestion caused by dense crowds, and the ship motion, heeling angle of a sinking ship and so on (Liu & Luo, 2012). For this reason, Liu & Luo (2012) proposed a concept of "equivalent route", where all the influence factors are treated as penalty terms, and assigned with weight parameters as penalty coefficients, thus generating an "equivalent length". Minimizing the equivalent length is the objective of the evacuation model in their research. The formula of the "equivalent length" is actually a multi-criteria objective function with the one-dimensional approach.

Karabuk & Manzour (2019) proposed a stochastic multi-stage optimization model to deal with the uncertain track of hazardous weather event, such as tornados. Their model incorporates a multi-criteria objective function with three criteria, number of injuries, redundant evacuations and evacuation time. The solution is optimized by assigning weights of the three criteria in lexicographic order. Moreover, in order to study the management of aggregate-level demand of vehicle-based massive evacuation of short-notice disasters like hurricanes and wild fire, Bish & Sherali (2013) introduced a network evacuation model, with a lexicographic ordered objective function, that includes criteria of network clearance time and total duration of evacuation routes. In addition, Non-Dominated Sorting Genetic Algorithm II (NSGA-II) is also useful to deal with multi-objective model of earthquake planning management (Ghasemi et al, 2019).

3.2. Research on Evacuation Models Simulation

Implementing a decision model into simulation is an effective way to evaluate the model, and the results can be used to examine and update the model.

In pedestrian-based evacuation models, the simulation of pedestrians movement is particularly important. According to the scale of the model, evacuation models are mainly categorized as macroscopic, microscopic and mesoscopic (Li et al., 2019). Macroscopic models treat the crowd as a fluid stream and do not consider the characteristics of individual evacuees. In mesoscopic models, the crowd is regarded as gas dynamics with individuals distributed according to their position and velocity. However, microscopic models deal with each individual evacuee as a research object and take individual features into consideration. According to Kim et al. (2019), an agent-based model is designed to reflect individual characteristics, which tracks each individual using coordinate but suffers from long computation time. Li et al. (2019) pointed out that microscopic models can measure the pedestrian movement most accurately, but naturally at a cost of computational efficiency.

In the related literature, several types of mathematic microscopic models have been developed to do pedestrians movement prediction or replication, and the most widely used one with evacuation problem is cellular automata (CA) model, which is featured as efficient, scalable and implementable (Li et al., 2019). The concept of cellular automata was introduced by Von Neumann in 1950s, defined by a set of rules. The CA model is a dynamic system where space is divided into grids with limited capacity, and it is able to simulate the spatial-temporary development of complicated systems (Li et al., 2019). Geng et al. (2019) proposed a cellular automata model to simulate the pedestrian-based evacuation under the condition of adverse sight conditions. Fu et al. (2018) investigated the exit selection behaviour during evacuation by integrating least effort algorithm with a CA model. Muller et al. (2014) used a extended CA model to study the group behaviour during evacuation process. In order to deal with the uncertainty of pedestrians under adverse sight conditions, Geng et al. (2019) proposed a cellular automata model to simulate the evacuations.

3.3. Uncertainty during Evacuation

Another major aspect in the literature review is about uncertainty in the evacuation. Actually, there are several different terms to explain the handling of uncertainty, including static versus dynamic, deterministic versus stochastic or robust. These terms are widely used in the relevant literature, and very often, the definition of one term varies from article to article. In other words, sometimes two different terms in different articles actually mean the same. For this reason, in this thesis, the relevant terms are firstly defined to prevent potential confusion, and in the following of this section, the use of these terms is consistent to the definition.

First of all, uncertainty is defined as “lack of predictability of outcomes” (Wallace, 2005). For example, the development of a fire disaster on board is actually a source of uncertainty. If not considering the uncertainty involved in the future development, a model is deterministic, and some people also call it as a static one. However, if a model takes uncertainty into consideration, it is then dynamic or stochastic. In this thesis, the terms “deterministic” and “stochastic” are used, rather than “static” and “dynamic”, to describe the two kinds of model. In addition, the term “dynamic” is also used in this thesis, interchangeably with the term “stochastic”, to describe changing situations, for example, the dynamic of evacuees’ movement. Indeed, the meaning of “dynamic” is somewhat similar to that of “uncertain”, and in this thesis, both are used depending on different occasions.

Generally, the evacuation models in the literature can be divided into two categories, deterministic and stochastic, for both evacuees and hazardous situations. In the study of Cisek & Kapalka (2014), when routing for emergency evacuations, the basic pre-disaster evacuation plan for buildings and other public places is based on fixed data of hazard and even not considering the evacuees. However, deterministic modelling does not change the stochastic nature of a problem (King & Wallace, 2012). Emergency evacuation is usually conducted under uncertainty due to unprecise and incomplete information about the risk of disaster and the behaviour of evacuees, because the development and impact of the disaster and the evacuees behaviour are somehow unpredictable, and more precisely, hard to predict. According to Ronchi et al. (2014), in terms of fire safety engineering and modelling, uncertainty mainly comes from three aspects, intrinsic uncertainty, model input uncertainty and measurement uncertainty. Typically, for evacuation modelling, the uncertainty of evacuees behaviour and hazardous situation are two main parts of model input uncertainty. Therefore, in some articles, the evacuation models consider both the uncertainty from the hazard and the personnel movement.

For instance, Cisek & Kapalka (2014) introduced an evacuation model that acquires dynamic data of both evacuees and hazardous situation development collected by various detectors and sensors. Li & Zhu (2018) made a route optimization evacuation model combined with a dynamic risk assessment of fire, based on the results of numerous simulations and focused on several risk indicators such as toxic gas, temperature and thermal radiation. Zhu et al. (2009) considered dynamics of evacuees' walk speed, mental condition and route selection caused by fire disaster development, proposing a time-varying smoke parameter based on simulations. Lim et al. (2015) proposed a real-time evacuation re-routing approach when the original route is affected by disaster.

With respect to traffic flow in the evacuation problem, in deterministic models, traffic flows are assumed to be predictable while in stochastic ones, future traffic flows are inscrutable and hard to predict (HCM, 2010). Bayram (2016) argued that despite the fact that deterministic models can generate relatively good estimation for planning purposes, compared to stochastic ones, they are not able to capture the dynamics of evacuees and hazardous situations. However, Bayram (2016) also pointed out that it is challenging for optimization-based stochastic models to be implemented into large-scale evacuation cases as the computation speed could be a problem. For this reason, in the existing studies, stochastic evacuation models are mainly heuristic or simulation-based. For instance, Shin et al. (2019) developed four mathematical models based on the discrete time dynamic network flow to provide the optimal routes for evacuees but were faced with a problem of long computation time for large-size network, so they finally developed a heuristic algorithm. In addition, Lim et al. (2012) also developed an evacuation scheduling algorithm to expedite the solution process when faced with large network computations.

Dynamic traffic assignment (DTA) models describe features of dynamic traffic flows, and can be generally categorized into dynamic user equilibrium (DUE) and dynamic system optimal (DSO) models. Alam & Habib (2019) adopted a DTA process to capture the temporal variations of travel time during emergency evacuations. In addition, Bayram (2016) stated that, dynamic evacuation models in existing research mainly originate from two kinds of models, one is cell transmission model (CTM) proposed by Daganzo (1994), which is based on the DTA model. The other one is models based on dynamic network flows. For instance, Kimms & Maassen (2011) introduced an extensive model of CTM that incorporates the rescue team contraflows into evacuation modelling. Zhang et al. (2015) proposed an evacuation model that integrates CTM with the Macroscopic Fundamental Diagram for city traffic networks. Capote et al. (2012) collected data on behavioural uncertainty of passengers in a train during emergency. Similarly, Li & Ozbay (2015) pointed out that most of the existing studies on evacuation planning only focus on exogenous uncertainties, such as the damage caused by disasters, but ignore endogenous uncertainties, such as traffic network flow related issues. For this reason, Li & Ozbay (2015) incorporated probability density function of endogenously determined factors on the base of the CA macroscopic model. In addition, Cisek & Kapalka (2014) put forward a evacuation model that dynamically react to evacuees movement direction and detect the hazard situation, suggesting real-time directions for evacuees with signages in a building. Ghasemi et al. (2019) dealt with uncertainty by implementing their earthquake evacuation model to multiple scenarios. Lim et al. (2012) constructed a time-expanded version of deterministic model by dividing the whole time period into intervals, so that they could deal with the dynamic nature of the optimization problem of evacuation planning. Zhang et al. (2017) carried out a computer simulation to sample the uncertain factors in fire emergency evacuation by employing a possibility density function.

3.4. Cruise Ships Specific Research

As also mentioned previously, there are some influencing factors typically for the evacuations of cruise vessels, and which should be considered when modelling to guide the evacuations.

Chen et al. (2016) pointed out that the pedestrian movement on ships is different from that on a stable horizonal floor due to the water motion, so they proposed an agent-based pedestrian evacuation model considering the special features of evacuation on ships. Kim et al. (2019) took the sinking accident of the Sewol as an example, studied the influence of heeling angle on passenger evacuation.

3.5. Summary of Literature Review

Summing up the literature review section, there is a large number of existing papers about evacuation based on several kinds of methodology, mainly optimization and simulation. However, existing research that focuses on evacuation that take place on cruise vessels is still rare. As mentioned previously, there is a difference between evacuation on ships and on normal flat floors because of the periodic wave, ship motion and probable heeling and sinking due to the accident. So it is inadequate to simply implement evacuation models that are designed for evacuations happened in buildings or open areas. For this reason, cruise specified features should be considered when modelling for emergency evacuation on cruise vessels. For instance, the influence on walking speed of evacuees on ships during fierce shakes in storm; the influence on evacuees' walking speed on ships during heeling and sinking; the influence on the release of lifeboats during severe heeling of ships. Furthermore, a considerable proportion of existing research does not consider the dynamics and uncertainty of evacuees or hazard, or both. However, if the dynamic and uncertain factors are not considered, the evacuation model developed could be meaningless to implement into real cases. But, optimization-based dynamic models have computational difficulties, as previously mentioned. So implementing dynamic factors into evacuation modelling is challenging and calls for trade-offs and more advanced models.

In addition, a majority of previous research on evacuation planning ignore individual differences of evacuees, which can have a huge influence on the evacuation process. For example, the walking speed and movability of passengers of different age, gender and physical condition are different. Especially for passengers on cruise vessels, a considerable proportion of them is aged population, some of which may be even disabled and use wheelchairs. Accordingly, in this thesis, evacuees will be categorized according to their individual characteristics, mainly age, walking speed and movability. In terms of route selection, evacuees from different categories will also be considered differently. For instance, the evacuation routes that contains stairs or narrow corridors would be inapplicable for wheelchair users.

Furthermore, typically for the studies of evacuation modelling based on vessels, an important technical premise of feasible wireless data communication within internal vessel is ignored or missed. In fact, if without this essential technical premise, all the relevant models developed for vessel evacuation guiding would be meaningless because they could not be implemented in real cases. The reason is that steel stops radio propagations, and modern huge vessels are almost all with steel structures, and actually, all rooms, halls and corridors are individual confined steel environments. Therefore, without cables, the communication between different rooms on a vessel is technically infeasible. Accordingly, further relevant research on this topic should also take this technical problem into consideration.

4. Methodology

In this section, firstly the technical premise and support of the proposed model is introduced. Afterwards, the methodology of the modelling system is presented, which involves optimal route determination, evacuees guiding, and the dynamics and uncertainty of both evacuees movement and hazard development. As demonstrated in Figure 1, the core of the modelling system consists of a route determination system and an evacuation guiding system. The initial inputs are data of evacuees and the layout of the cruise vessel. In addition, data of evacuees movement and hazardous situation development are continuously acquired and updated by the evacuees tracking system and hazard detection system, and input into the core systems of the model over time. Finally, the proposed model is implemented to a simulation, and based on the simulation results, possible adjustments are made to the modelling.

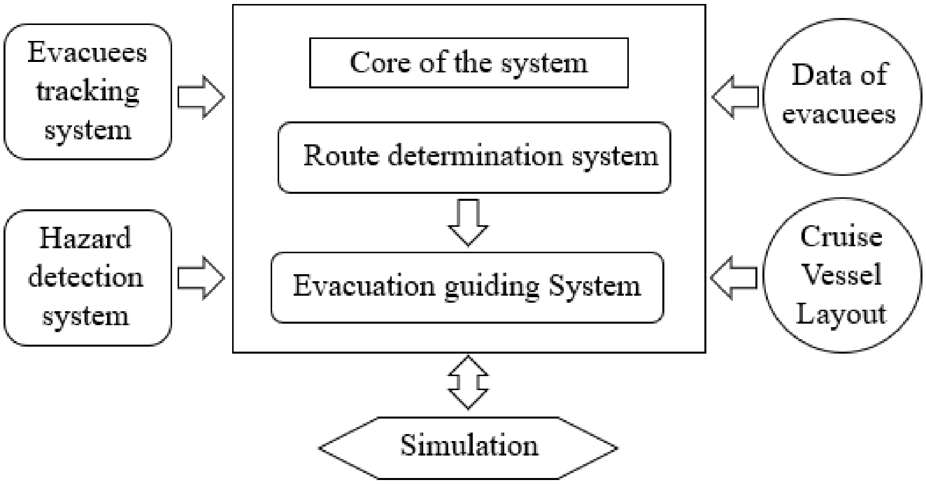

Figure 1: Flow chart of methodology for the modelling system

4.1. Technical Premise and Support

As mentioned in Section 3.5, the existing studies on evacuation on vessels are rare, and among those, an important shortcoming is the failure to mention the implementability of whatever models or methodologies that were come up with. In other words, most of the models are actually not able to be implemented into real cases, due to the technical barriers. In fact, the feasibility of wireless data communication in vessels is a crucial premise when modelling the evacuation guiding cases on vessels. According to ScanReach (2019), up until now cabling has been required in data transfer and communication in confined steel environments, such as industrial plants, offshore platforms and ships. This means that, if cables are burned off by the fire disaster, or the electricity power is interrupted on board, the data communication in the internal vessel is also cut down. It is the failure of data communication on board makes the evacuation models proposed in existing relevant studies weak to implement in practical cases.

Therefore, in the proposed methodology in this thesis, the feasibility of wireless data communication in confined steel environments is a necessary technical premise. Fortunately, a breakthrough sensor mesh technology has been developed by ScanReach, which now makes the wireless data transfer possible in confined steel environments. This technology is also a life-saving technology, which provides instant personnel control, allowing precise and immediate involvement of rescue team, during emergency situations onboard ships (ScanReach, 2019). ScanReach proposed a special wristband that contains an intelligent chip wearing on each passenger on board, and the chip is personal identified. Also, another equipment of sensors is installed in each room and each node of corridors on board, which receives the instant signal from wristband wearing on each passenger, thus locating and tracking each passenger over time. Because the wristband is individually identified, for example, it is possible to know exactly who is in which room and who is stuck. The real-time data of passengers are collected by the sensors and then transferred to the central unit of data processing. The communication method is actually through "talking each other" between neighbouring sensors, and is realized by the confidential core technology of ScanReach.

In addition, from the meeting with representatives of ScanReach, more detailed functions of their products were learned. The sensors can be plugged into normal power sockets to get powered all the time, and it is backed up by additional battery which can last for 36 hours during possible power blackouts under hazardous situations. In addition, the chips of ScanReach is intelligent enough to detect the condition of the passenger who is wearing it. For instance, it can detect the body temperature and even subtle movements as indications of the life signs of the passenger, and is also able to detect the falling of passengers, with the movement detection function carried in the wristband chip. Based on the number of meters the chip has fallen, even normal falling down and falling from stairways can be differentiated and inferred. Furthermore, the movement detection function can also detect the passengers who are trapped by the disaster. Finally, the installation of the products from ScanReach is adaptable to both existing vessels and those under construction.

With the technical support from ScanReach, the following introduced modelling system is technically implementable.

4.2. Initial Data Input

According to Figure 1, the data of the cruise vessel layout is firstly imported, based on which the whole evacuation process is carried out. The data of cruise vessel layout includes but is not limit to, the structure of the vessel, function of different facilities, width and length of corridors, and capacity of lifeboats. In addition, the data of the evacuees should also be input at the beginning, which are mainly the initial location, the movability and walking speed of each evacuee.

4.3. Hazard Detection System

According to Cisek & Kapalka (2014), the hazard detection system is consisted of detectors, which identify and locate the hazard. Similarly, in the proposed methodology of this thesis, the hazard detection system consists of sensors that can detect key elements and factors of a given type of disaster. For simplification, in this thesis a fire disaster is supposed as the typical type of hazard. Therefore, the sensors are supposed to be able to detect the temperature, smoke, flame and concentration of toxic gases that are generated by a fire disaster, such as carbon monoxide (CO). In addition, a fire disaster can also be detected by the failure of one or several sensors in specific areas (Cisek & Kapalka, 2014). The sensors should be implemented evenly in each cabin, hall and corridor, and the information gathered by each sensor can indicate the real-time hazardous situation. The proposed hazard detection function of sensors could be implemented to the existing technology of ScanReach, as introduced in Section 4.1.

4.4. Evacuees Tracking System

The idea of having an evacuees tracking system can also be found in Cisek & Kapalka (2014), where the movement of evacuees are realized by counting the numbers of evacuees in one specific room or corridor, and the movement is determined by the difference of evacuees numbers over two consecutive time intervals. However, it is impossible to know exactly who is in which room and who has moved to other places. Correspondingly, an improvement has been made in this thesis, that the proposed movement measurement system can know exactly where each evacuee is during the whole evacuation process. Nowadays each passenger on the cruise ship wears a wristband, which is used to show the identity, open the cabin door and so on. The idea is that, the wristband can be updated to involve the intelligent chip developed by ScanReach, which is able to communicate with the nearest sensor on the wall, thus locating each individual passenger. The proposed movement measurement is realized by the real-time tracking of each evacuee. However, the movement tracking system is not like GPS, and is not able to know the exact coordinate of each passenger, and is only able to know, for example which cabin the evacuee is in. The proposed wristband is also able to differentiate the evacuees who do not move, is stuck or dead. Then the rescue staff can be sent to those evacuees in trouble according to specific situations. All these functions are realizable with the ScanReach technology introduced in Section 4.1.

4.5. Route Determination System

With the input data of the cruise vessel layout and evacuees, with the tracking information of the movement and instant location of each evacuee over time, and with the real-time information of hazardous development that gathered by the hazard detection system, the core route determination system is able to decide an optimal route for each evacuee on board, according to a certain model. This model is going to be thoroughly explained in Section 5.

4.6. Evacuation Guiding System

In the research of Cisek & Kapalka (2014), the evacuees are guided by signals on the wall or other devices that can simply show the directions to evacuate. However, this method not only could cause congestion because all the people at one node will follow one same signal flow into one way, maybe a narrow corridor, but also ignore the individual difference of each evacuee. For instance, as mentioned in Section 3.5, some passengers on cruise ships could be disabled, therefore the route contains stairs and narrow corridors cannot be suggested to such kind of passengers. In addition, consider the development of hazard, for example, one route will possibly be blocked in 5 minutes due to the spread of fire, and according to the walking speed of passengers in different categories, young people can be suggested to go through that route rather than aged people, because younger ones have more chance to pass that route within 5 minutes. For these reasons, another improvement is made to the guiding approach, that is, the proposed evacuation model will suggest differentiated optimal routes for different groups of evacuees. However, it is a key problem about how to inform the optimal route to each evacuee. The idea of using signals from Cisek & Kapalka (2014) could be a solution. For example, signals of different colours can be used to guide people in different groups. The instructions of the signals are generated by the route determination system in Section 4.5, and can change over time with updating of optimal routes. Each passenger is also assigned a typical colour on his or her wristband, according to his or her movability and walking speed. If an evacuee notices that the colour indicated on his or her wristband is red, he or she will only follow the signals in red, for instance, red arrows showing on a LED screen. The guiding signals are supposed to be shown on battery backed up LED screens that installed together with the sensors. However, the signals should better not confuse the evacuees, for example, make the evacuees turn back along the corridor they just passed through, unless it is necessary due to the updated hazardous situations.

However, in this thesis, all the passengers are assumed to strictly follow the guiding, which is too idealized and without considering the uncertain evacuees behaviours. The detailed discussion of the evacuees behaviours will be presented in Section 7.1.

4.7. Summary of Methodology

To conclude this section, in this thesis, a methodology system to realize the evacuation guiding under emergency situations on cruise vessels is proposed. The initially input of data is the layout of vessel and the distribution, movability and walking speed of evacuees.

Then the evacuees tracking system and hazard detecting system are capturing and transferring the real-time data to the core system of the model, and these two systems are technically supported by the technology of ScanReach. Then, in the core of this model is the route determination system, which could be developed into the products of ScanReach, and the optimal route generated is suggested to the evacuees with signals, which is also supported by the wireless data transfer technology in confined steel environments of ScanReach. Therefore, the cruise vessel based evacuation guiding model generated by the proposed methodology in this section is technically implementable to the real world cases.

5. Proposed Model

5.1. Sets and Parameters

Table 1: Sets in the proposed model

Sets	
Symbol	Description
V	Collection of vertices, representing a logical space (e.g. a cabin, a hall, a doorway and an intersection of corridors).
E	Collection of edges between nodes (e.g. a corridor and a stairway), which can also be expressed as (u,v), where $u,v \in V$.
G	$G = (V,E)$, a graph consisted of the vertices and edges, representing the structure of ship layout.
S	Sink nodes, representing lifeboats in this case. $S \subseteq V$.
T	Collection of time intervals.
I	Collection of evacuees.
X	Collection of young adults and teenagers among the evacuees, $X \subseteq I$.
Y	Collection of elder passengers and children among the evacuees, $Y \subseteq I$.
Z	Collection of wheelchair users among the evacuees, $Z \subseteq I$.

The set V represents the set of vertices in the ship layout, and the vertices can be different facilities, for example, a cabin, a room, a dining hall or a lifeboat. E is the set of edges link between the vertices, and an edge can be a corridor or a stairway. In the algebras in this thesis, an edge is expressed as $(u,\ v)$, where $u,\ v\ \in\ V$. G is the graph of network consisted of all the vertices and edges, representing the structure of the layout of a cruise ship. The set S represents the collection of sink nodes in the network, typically lifeboats in this case, and is a subset of V. Parameter C_s is the capacity of a sink node s, in this thesis typically means the maximum number of passengers on the lifeboats. Parameter $l(u,\ v)$ and $W(u,\ v)$ represent the physical length and width of an edge $(u,\ v)$, and the width is measured with the actual passage width of a door in its fully open position and the handrail for stairways and corridors (IMO, 2016). In addition, by multiplying these two parameters we get the parameter $A(u,v)$, meaning the space of each edge $(u,\ v)$. Parameter $L(u,\ v)$ is the equivalent length of an edge $(u,\ v)$ at time t, and the detailed explanation of the concept equivalent length follows below. T is defined as the set of time intervals. The set I is the collection of evacuees on board, and as what mentioned in Section 3.5, during the evacuation planning on cruise ships, evacuees will be categorized according to their individual characteristics, mainly age, walking speed and movability. Accordingly, the evacuees are divided into three categories, which are three subsets of I, namely X, Y and Z. X is the collection of young adults and teenagers, who have full movability at a relatively high walking speed. Subset Y includes the elder ones and children among the passengers, who also have full movability but with a relatively low speed compared to those in subset X. Finally, the wheelchair users are categorized into the subset Z, who are not able to move freely on some edges, mainly narrow corridors and stairways, and whose moving speed is even lower than the passengers in the other two categories.

Using binary parameters b_y and b_z can express the passengers in each groups. If $b_y = b_z = 0$, the passenger is from group X. $b_y = 1$ and $b_z = 1$ if the passenger is from group Y and Z, respectively. It is impossible that $b_y = b_z = 1$ at the same time, because a passenger cannot from both group Y and Z. Sp is the base speed of evacuees, which is equal to the speed of passengers in category X. In addition, for those in group Y and group Z, the moving speed are assumed to be 80% and 60% of the base speed, respectively.

Table 2: Parameters in the proposed model

Parameters	
Symbol	Description
C_s	Sink capacities (maximum load number of passengers on the life boats).
$l(u,v)$	Physical travel length of an edge(u,v).
$L(u,v)_t$	Equivalent length of edge (u,v) at time t.
$W(u,v)$	Clear width of an edge (u,v).
$A(u,v)$	Space of an edge (u,v).
$P_x(u,v)_t$	Number of evacuees from group X in edge (u,v) at time t.
$P_y(u,v)_t$	Number of evacuees from group Y in edge (u,v) at time t.
$P_z(u,v)_t$	Number of evacuees from group Z in edge (u,v) at time t.
$P(u,v)_t$	Total number of evacuees in edge (u,v) at time t.
$D(u,v)_t$	Density of evacuees in edge (u,v) at time t.
F_s	Specific flow $(p/m/s)$ is the number of escaping people past a point in the escape route per unit time per unit of clear width of the route involved.
Sp	Base speed of evacuees.
$TT(u,v)_t$	Travel time along edge (u,v) at time t.
$f(u,v)_t$	Number of passengers enter the edge (u,v) at time t.
$ff(u,v)_{(m,n)}$	Number of passengers enter the edge (u,v) at time m and leave the edge at time n.
$b_o(u,v)_t$	Binary parameter. 1 if there is an obstacle in edge (u,v) at time t, 0 otherwise.
$b_s(u,v)$	Binary parameter. 1 if edge (u,v) is a stairway, 0 otherwise.
$b_e(u,v)$	Binary parameter. 1 if edge (u,v) is an elevator, 0 otherwise.
$b_n(u,v)$	Binary parameter. 1 if edge (u,v) is inapplicable for wheelchair users, 0 otherwise.
b_y	Binary parameter. 1 if the evacuee is an elder citizen or a child, 0 otherwise.
b_z	Binary parameter. 1 if the evacuee is on wheelchair, 0 otherwise.

Parameters $P_x(u,v)_t$, $P_y(u,v)_t$ and $P_z(u,v)_t$ are the numbers of evacuees from group X, Y and Z, respectively, in an edge (u,v) at time t. The sum of the three numbers is $P(u,v)_t$, which means the total number of evacuees in an edge (u,v) at time t. By dividing $P(u,v)_t$ by the space parameter $A(u,v)$, we get the density parameter $D(u,v)_t$ of each edge (u,v) at time t. However, the fact that the wheelchair users will take more room than other people should considered as well. Therefore, a wheelchair user is assumed to take up twice the space of a normal passenger, and the calculation methods is:

$$D(u,v)_t = \frac{P_x(u,v)_t + P_y(u,v)_t + 2P_z(u,v)_t}{A(u,v)} \tag{1}$$

$TT(u,\ v)_t$ is the travel time along an edge $(u,\ v)$ at time t, and is calculated by dividing $L(u,\ v)_t$ by Sp and different for each passengers with different speeds:

$$TT(u,v)_t = \frac{L(u,v)_t}{Sp(1-0.2b_y-0.4b_z)} \tag{2}$$

Table 3: Values of initial speed as a function of density

Initial density D (p/m2)	Initial speed of persons (m/s)
0.00	1.20
0.50	1.20
1.90	0.67
3.20	0.20
>=3.50	0.10

According to IMO (2016), the moving speed of evacuees can be expressed as a function of crowd density, as demonstrated in Table 3. Based on the figures in Table 3, a piecewise linear speed function in terms of density is defined as followed in Equation 3:

$$\begin{array}{ll} Sp = 1.2 & 0 \leqslant D < 0.5 \\ Sp = 389/280 - 53/140D & 0.5 \leqslant D < 1.9 \\ Sp = 441/325 - 47/130D & 1.9 \leqslant D < 3.2 \\ Sp = 19/15 - 1/3D & 3.2 \leqslant D < 3.5 \\ Sp = 0.1 & D \geqslant 3.5 \end{array} \tag{3}$$

$b_o(u,\ v)_t$ is the binary parameter for obstacles within an edge $(u,\ v)$ at time t. $b_o(u,\ v)_t$ equals to 1 if there is an obstacle in an edge $(u,\ v)$ at time t, and 0 otherwise. The "obstacle" can be anything that makes the edge out of use, for example, blocked by real obstacles, ruined by the disaster, and being assessed as dangerous because of toxic gas or heavy smoke, and so on. The data of smoke, toxic gas, flame and temperature can be collected by the sensors installed on the wall and communicated to the central unit for data processing. $b_s(u,v)$ equals to 1 if an edge (u,v) is a stairway, and 0 otherwise. $b_e(u,v)$ equals to 1 if an edge (u,v) is an elevator, and 0 otherwise. $b_n(u,v)$ equals to 1 if an edge (u,v) is inapplicable to wheelchair users, and 0 otherwise. In this thesis, mainly two situations exist where an edge is inapplicable to wheelchair users, one is when the edge is too narrow to pass with a wheelchair, assuming narrower than 1.2 meters. The other is when the type of an edge is impossible to pass with a wheelchair, mainly stairways. Edges that are elevators could be the only choice for wheelchair users to go upstairs or downstairs, but under some emergency circumstances, the elevators may be out of use as well. In this thesis, using the elevators are prohibited during an emergency evacuation for evacuees in group X and Y, but it could still be used by wheelchair users as it is assumed to be the only way for them to go upstairs or downstairs. However, if the wires to support the elevators are ruined, the elevators are therefore shut down, and wheelchair users are not able to go upstairs or down stairs without help.

F_s is specific flow (p/m/s), which is defined as the number of escaping people pass a point in the escape route per unit time, per unit of clear width of the route involved (IMO, 2016). $fi(u,v)_t$ is the number of passengers that enter the edge (u,v) at time t, while $fo(u,v)_t$ is the number of passengers leave the edge (u,v) at time t. $ff(u,v)_{(m,n)}$ is the number of passengers enter the edge (u,v) at time m and leave the edge at time n. Moreover, m equals to the specific time t while $n=m+TT(u,v)_t$. With $fi(u,v)_t$, $fo(u,v)_t$ and $ff(u,v)_{(m,n)}$, the parameter $P(u,v)_t$ can be calculated:

$$\begin{gathered} fi(u,v)_t = ff(u,v)_{(t,n)} \qquad \forall\,(u,v)\in E,\ t,n\in T,\ n>t \\ fo(u,v)_t = ff(u,v)_{(m,t)} \qquad \forall\,(u,v)\in E,\ m,t\in T,\ t>m \\ P(u,v)_t = P(u,v)_{t-1} + fi(u,v)_t - fo(u,v)_t \qquad \forall\,(u,v)\in E,\ t\in T,\ t\geqslant 1 \end{gathered} \tag{4}$$

However, in practice, the location of each evacuee as well as the parameter $P(u,v)_t$ are supposed to be adjusted according to the instant data collected by the evacuees tracking system, as the real situation are always different from the idealized calculations.

5.2. Optimal Route Determination

The objective of evacuation planning is usually to find an evacuation route that takes shortest time, however, the route that consumes least time is not necessarily equivalent to the shortest-length route, because the difficulty of passing different kinds of edges varies, for instance passing a corridor is obviously easier than passing a stairway, and there are also influence from cruise-specific factors on the walking speed on board (Liu & Luo, 2012). For this reason, in this thesis, the concept of "equivalent length" is introduced, as discussed in Section 3.1.2. The concept of "equivalent length" is originally used in the evacuation planning in high-rise buildings, but can be adapted to the evacuation planning on cruise ships as well. Equivalent length means that, all the factors that can influence the difficulty to pass a certain path are represented by penalty terms, adding to the real length, thus resulting the "equivalent length" (Liu & Luo, 2012). The formula of equivalent length is following:

$$L_i = (1 + wc + \rho\varpi_p + \varpi_e + k_l k_i) l_i \tag{5}$$

where L_i represents "equivalent length" for each facility i within the evacuation route; c means the percentage volume of harmful gases (usually CO) and with w as the penalty coefficient; ρ means density of crowd (number of persons per m^2), and ϖ_p is the coefficient of walking difficulty among crowd; ϖ_e is the coefficient of walking difficulty considering the obstacles on the way of evacuation; k_l represents the difficulty coefficient of passing different types of facilities, for example, the difficulties to pass a corridor, a stairway and a big room vary; k_i represents the danger coefficient of different areas; l_i represents the real length of evacuation route.

Basically, the definition of "equivalent length" is to add penalties to various factors that have influence on the difficulty to pass the certain evacuation route. For example, if the route is hard to pass due to some reasons, such as congestion with dense crowd, the route will be made “longer” by calculating the so-called equivalent length, then the route is more “expensive” for the evacuees to pick during the evacuation. However, the real length of a route will never change.

5.2.1. Definition of Equivalent Length

In the model proposed in this thesis, a similar penalty-adding approach will be adopted to calculate the equivalent length of each edge in the network over time. However, the formula should be modified to adapt to the typical case studied in this thesis.

Firstly, the penalty term of harmful gas, wc, can be viewed as a special type of obstacle and simplified from the formula. If the concentration of harmful gas in an edge, such as carbon monoxide (CO), is higher than a critical value that can do harm to lives of human beings, then it can be deemed as an obstacle within the edge. In fact, the term wc can be retained if reasonable function of penalty coefficient w is defined. For instance, the factors to be considered include but not limit to, the severity of symptoms when exposing to certain concentration of CO, the time of exposure, and moreover, the sensitivity to CO of passengers of different ages, gender and health condition and the breath frequency and volume when running to evacuate. For this reason, obviously, the determinisation of the coefficient w is out of the scope of this thesis, and for simplification, the penalty term wc is viewed as one kind of obstacles in the route. Furthermore, as discussed in Section 5.1, an “obstacle” can be anything that makes the edge out of use, including but not limited to being blocked by the obstacles, ruined by the disaster, and assessed as dangerous because of toxic gas or heavy smoke, and so on. In this thesis, the data of smoke, toxic gas, flame and temperature are assumed to be collected by the sensors installed on the walls and communicated to the central unit for data processing. For this reason, all these influence factors from fire disasters are classified as “obstacles”, and the corresponding penalty coefficient ϖ_e is set to a very large number, thus making this edge infinitively expensive for the evacuees to pick.

Secondly, the term k_l which represents danger coefficient of different areas is also removed. It makes sense that the areas near the origin of fire are more dangerous than those far away from it. For this reason, similar to the penalty coefficient of harmful gas w, if a sensible definition of danger coefficient k_i can be worked out, for example, according to computer simulation of fire spread or any relevant theoretical or empirical knowledge, then this coefficient should be included. However, there are also complicated factors that should be taken into consideration when determine the function of k_i. Therefore, in this thesis, k_i is also not considered.

Thirdly, the penalty term k_l, which represents the difficulty to pass different kind of facilities, should be kept. In addition, this term is refined to mainly three different facilities, corridors, stairways and elevators. In this way, better adaption to the setting of different evacuees groups can be achieved, and detailed explanation is in the following contents. Crowd density penalty term should be kept as well.

The modified formula of equivalent length is as followed:

$$\begin{gathered} L(u,v)_t = l(u,v)\,(1 + \varpi_p D(u,v)_t + \varpi_o b_o(u,v)_t + \varpi_n b_s b_n(u,v) \\ + \varpi_e(1 - b_z) b_e(u,v)) \end{gathered} \tag{6}$$

where $L(u,v)_t$ is the equivalent length of the edge (u,v) at time t, while $l(u,v)$ is the physical length of each edge (u,v). $\varpi_p D(u,v)_t$ is the penalty term of crowd density, where $D(u,v)_t$ is the density of passengers in edge (u,v) at time t, with the penalty coefficient ϖ_p multiplied. How to obtain $D(u,v)_t$ was discussed in Equation 1 in Section 5.1. In terms of the value of ϖ_p, according to Liu & Luo (2012), the penalty term $\varpi_p D(u,v)_t$ can be represented by the reciprocal of walking speed, that is, $\varpi_p D(u,v)_t = 1/Sp$. In addition, the relationship among walking speed Sp, specific flow of persons Fs and crowd density D is $Sp = Fs/D$. For this reason, $\varpi_p D = 1/Sp = D/Fs$, and thus $\varpi_p = 1/Fs$.

Table 4: Values of initial specific flow as a function of density

Initial density D (p/m^2)	Initial specific flow Fs (p/m/s)
0.00	0.00
0.50	0.65
1.90	1.30
3.20	0.65
⩾3.50	0.32

In addition, the value of Fs is determined by the value of crowd density D, and in Table 4 is the values of initial specific flow as a function of density (IMO, 2016). According to the values in Table 4, a piecewise linear Fs function of crowd density D is fit, as showed in Equation 7.

$$\begin{array}{lr} Fs = 1.3D & 0 \leqslant D < 0.5 \\ Fs = 117/280 + 13/28D & 0.5 \leqslant D < 1.9 \\ Fs = 2.25 - 0.5D & 1.9 \leqslant D < 3.2 \\ Fs = 4.17 - 1.1D & 3.2 \leqslant D < 3.5 \\ Fs = 0.32 & D \geqslant 3.5 \end{array} \tag{7}$$

In addition, the second penalty term $\varpi_o b_o(u,v)_t$ is about obstacles in the route. As also discussed in Section 5.1, binary parameter $b_o(u,v)_t = 1$ if the edge (u,v) is out of use at time t, while 0 otherwise. The penalty coefficient ϖ_o set to infinity, and if the edge is out of use, the equivalent length will become infinitely long, thus avoiding the evacuees to pick it.

The third penalty term $\varpi_s b_s(u,v)$ refers to the penalty on extra difficulty to pass a stairway rather than a flat corridor. Binary parameter $b_s(u,v) = 1$ if the edge (u,v) is a stairway, otherwise 0. The penalty coefficient ϖ_s can be determined by different maximum specific flow passing different types of facility, which are shown in Table 5 (IMO, 2016). If the facility to pass is a stairway to go up, the value of ϖ_s can be estimated as 0.32, which is calculated from $(1.3 - 0.88)/1.3$. Similarly, if the facility to pass is a stairway going down, $\varpi_s = (1.3 - 1.1)/1.30 = 0.15$. If unsure about the direction of stairways, penalty coefficient can be estimated with the average of maximum Fs downstairs and upstairs, that is, $\varpi_s = (1.3 - 0.5(1.1 + 0.88))/1.3 = 0.24$.

Table 5: Values of maximum specific flow

Type of facility	Maximum specific flow Fs (p/m/s)
Stairs (down)	1.10
Stairs (up)	0.88
Corridors	1.30
Doorways	1.30

The fourth penalty term $\varpi_n b_z b_n(u,v)$ is designed to add penalty on the edges inapplicable to wheelchair users. $b_z = 1$ if the evacuee is on wheelchair, and 0 otherwise; $b_n(u,v)_t = 1$ if the edge (u,v) is inapplicable to wheelchair users, and 0 otherwise. The penalty coefficient ϖ_n should also be set to infinity, thus making the routes inapplicable to wheelchair users infinitively “long” for passengers on wheelchairs, thus avoiding involving such edges in the evacuation routes.

The fifth penalty term $\varpi_e(1 - b_z)b_e(u,v)$ adds a penalty on the edges which are elevators. As stated in Section 5.1, $b_z = 1$ if the evacuee is on wheelchair, 0 otherwise. Therefore, $1 - b_z = 0$ if wheelchair users, 1 otherwise. $b_e(u,v) = 1$ if the edge (u,v) is an elevator, 0 otherwise. Coefficient ϖ_e is also infinite. This penalty term can be interpreted as, during emergencies, only wheelchair users are allowed to use elevators, because usually elevators is the only way for them to go upstairs or downstairs, as also discussed in Section 5.1.

5.2.2. Selection of Algorithm / Theory

In this section, the deciding process of modelling the evacuation problem on cruise vessels is presented. The problem itself is non-linear, because the speed of evacuees is a non-linear function of the crowd density. In addition, there are several sources of uncertainty in this problem, mainly the development of the fire and the movement of evacuees. For these reasons, it is difficult and costly to directly model this problem. Next, several classical network flow problems in the field of graph theory is reviewed.

The evacuation process to model is actually a problem of quickest transhipment of three kinds of flows in a multi-source and multi-sink network, given the capacities of each sink node. The evacuees are initially dispersed in different nodes when an emergency hazard happens and evacuation begins. Therefore, the flows of evacuees are originated from difference source nodes. To model this problem, a classical problem in terms of flows in network are reviewed, which is called minimum cost flow problem.

According to Ford & Fulkerson (1962), the minimum cost flow problem is aimed to find the “cheapest” possible way to send certain amount of flow through a network. Specifically, as a special case of minimum cost flow problem, the Hitchcock problem is more similar to the problem of interest in this thesis, because it is also with the setting of multi-sink and multi-source. The Hitchcock problem was firstly introduced by Hitchcock (1941), where there are multiple sources of a commodity, each with a certain amount of supply, and also several sinks for the commodity, each with a certain amount of demand. Paths from each source to each node with a certain unit cost of the commodity, and the objective is to find the minimum cost transportation route that can satisfy the demand of a commodity. In addition, the minimum cost flow problem is equivalent to the shortest path problem if no capacity constraint on edges, while it can also be reduced to maximum flow problem if the costs to pass each edge is set to zero.

The case studied in this thesis is neither a problem of minimum cost flow nor a problem of maximum flow, because the cost is non-linear the obviously not zero. However, the problem to model in this thesis can be converted into the shortest path problem if the capacity constraint can be soften. In other words, the edge capacity is not treated as a hard constraint in this thesis. It is a common situation where the volume of flow exceeds the capacity of an edge, such as a corridor, during emergency evacuation, especially when a considerable part of the network breaks down due to the disaster. Hence, if we simply adopt a linear optimization algorithm and put a hard constraint on the capacities, it is very likely to end up no feasible solutions for some evacuees. In practice, a solution that abandons some of the evacuees due to the insufficient capacities is also inadvisable. For these reasons, in order to build a model more feasible and applicable to the real situation, the constraint of capacities will be treated as a soft constraint. That is, exceeding capacities of edges are allowed, but extra “penalty” will be added. This is the reason why the concept of “equivalent length” (Equation 6) is proposed in Section 5.2.1, where a penalty will be added to an edge at a time if the density of that edge is high. In fact, the idea of “equivalent length” is to linearize the non-linear parts in this problem, such as the non-linear speed in terms of the crowd density. Then, based on the equivalent length of each edge, the problem is simplified into the shortest route problem, and the Dijkstra algorithm is therefore adopted to determine the shortest route.

5.2.3. Dijkstra Algorithm

The Dijkstra algorithm is an efficient algorithm for finding the shortest path between two nodes, therefore, Dijkstra algorithm implied the idea of optimization, but not linear optimization. Dijkstra algorithm was introduced by Edsger W. Dijkstra in 1956, and published three years later. According to Dijkstra (1959), the problem of finding the path with the shortest length between two given nodes can be solved by Dijkstra algorithm.

The main idea of this algorithm is that, for example, one would like to figure out the shortest route from node P to node Q. Firstly, all the nodes are subdivided into three sets, namely A, B and C. The first node in set A is the starting node, for example, node P here. The first several nodes in set B are those directly linked to node P. The remaining nodes are in set C. Then, all the edges between the nodes are also subdivided into three sets, namely I, II and III. Set I is empty at the beginning, and all the edges between node P and its adjacent nodes are in set II. Set III is for the remaining edges. For instance, from node P, node R is the nearest one among all the adjacent nodes of P, then R is moved to set A and the edge between node P and R is moved to set I. Next, with P and R in set A, all the adjacent nodes of P and R are put in set B, and the edges connecting the nodes in set A and B are put in set II, and the shortest path from original node P to one of the nodes in set B are identified (not necessarily be direct path, transferring from node R is allowed), and this node is moved to set A and also the corresponding shortest edge to set I. Then, repeat the process until the target ending node Q is moved to set A, and at that time, the path of shortest route from node P and node Q is identified.

In fact, with respect to the algorithms to solve the problem of minimum length route among a network, there are also several other well-known algorithms, for instance, Floyd algorithm. However, Floyd algorithm is used to figure out the shortest routes between each two nodes. Therefore, for the model in this thesis, Dijkstra algorithm applies better, because only the shortest routes to the several sinks are needed to be worked out. Although there are multiple sources and therefore the algorithm would be run for multiple times, Dijkstra algorithm is still more efficient than Floyd one typically for the case studied in this thesis, as the latter calculates too much than needed.

On the other hand, whether to build a time-space model with the flows in network is also considered. But a time-space model is also not suitable to be used in the case of study, because the speed of traffic in the network is non-linear, and the equivalent lengths of edges to be used also vary from time to time. So, it is not a wise choice to use time-space idea in the case studied in this thesis.

5.3. Specific Steps of the Proposed Model

Finally, the evacuation guiding model on cruise vessels during emergency fire accident is worked out as followed. There are mainly 5 steps, where step 3 and step 4 are iterated over the time, until the available evacuation time is used up, or all the evacuees arrived the lifeboats.

Step 1: Translate the cruise vessel layout into a graph G of network, with vertices V and edges E. Input the parameters of each edge, including physical length and width, type of facility and availability. The location and capacity of each sink node (lifeboat in this case).

Step 2: Input the data of evacuees. For example, which category the evacuee belongs to, and the initial locations of them.

Step 3: Input the data of fire disaster situation over time. For example, when and where the fire is spread to, causing which edges become out of use.

Step 4: Calculate the equivalent length of each edge over time with Equation 6.

Step 5: Call Dijkstra algorithm to determine the shortest routes from each source node to each sink node, among which the shortest one is picked. Then with this shortest route, the next edge or node to go is extracted, with which the evacuees are guided when arriving that typical source node at that time.

Step 6: Update the data in step 1 and step 2 over time, and based on which iterate step 4 and step 5 as frequently as possible. The location of each evacuee should also be adjusted according to the instant data from the evacuees tracking system.

The proposed model divides the whole time span into multiple intervals, and iterate the step 4 and 5 for each period, thus handling the dynamic nature of an evacuation on a cruise ship under a fire emergency to some extent. However, this model does not really solve the uncertainty during emergency evacuations on cruise vessels, that is, it is to solve a sequence of linear and deterministic problems over time with the available information, but does not consider the future uncertainty. In the next section, this model will be simulated in a rolling horizon framework.

6. Simulation

In order to better illustrate the evacuation guiding model, it will be implemented for the third and fourth deck of the cruise vessel “Oasis of the Seas”, which is owned by Royal Caribbean International. “Oasis of the Seas” was placed in service in December of 2009. The ship is of 362 meters long and 47 meters wide, owns 16 decks and 2000 cabins, and is able to carry 5400 passengers and 2115 crew members.

In the simulation, the layout of the third and fourth decks of “Oasis of the Seas” are used, because the two decks are near to the engine room, which is most representative in terms of the structures (Liu & Luo, 2012). R is used as a tool to realize the whole simulation, and the R codes are attached in the appendix. The input data of the ship layout and evacuees is also in the appendix.

6.1. Process of Simulation

6.1.1. Network Graph Construction

The first step is to construct a network based on the layout of the third deck and fourth deck of “Oasis of the Seas”. As discussed in Section 5.1, the vertices are mainly cabins, doorways, and intersections of corridors, and the edges are mainly corridors and stairways. As demonstrated in Figure 2, there are 44 vertices in total, with vertex 41, 42, 43 and 44 as sinks. There are 63 edges in total, and the single lines between two vertices represent corridors, and double lines represents mainly stairways. However, in order to make it possible for wheelchair users to go upstairs and downstairs, edge (13,44) is assumed to be the only elevator between deck 3 and deck 4, and all the stairways to lifeboats, to be specific, edge (23,41), (38,42), (35,43) and (31,44) are also assumed to be accessible for wheelchair users. For example, these four stairways are assumed to be equipped with barrier-free rampways, and therefore also be able to pass wheelchairs. Another possible assumption is that the crew will help wheelchair users to pass the four stairways to get to the lifeboats. However, stairways (1,22), (3,24), (9,29), (11,32), (17,37) and (20,39) are stairways that are inapplicable to wheelchair users.

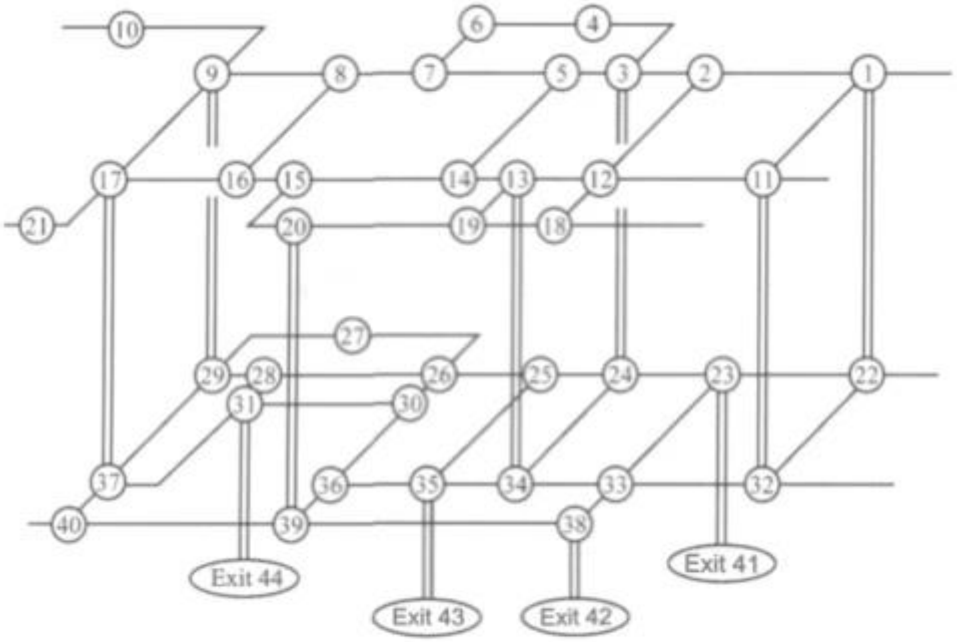

Figure 2: Network graph of the third and fourth deck of "Oasis of the Seas"

6.1.2. Input Data of Evacuees

In the simulation, it is set that 100 evacuees are in the whole network during the evacuation process. The data of initial location of each evacuee and which group each evacuee belongs to is input into the model. Basically, the 100 evacuees are dispersed randomly at each node in the network. It is assumed that the 100 evacuees consist of 35 young adults and teenagers, 60 elder citizens and children, and 5 wheelchair users. The capacities of each sink node, 41, 42, 43 and 44, are all assumed to be 25, and the total capacity is thus 100, which is exactly the same as the number of evacuees. However, in reality, it could be a problem of lack of lifeboat capacity, for example, some lifeboats are inaccessible to because of the spread of the fire. Moreover, if the cruise ship heels due to the disaster, it can also make some of the lifeboats difficult to release. In those cases, the model of evacuation guiding on cruise vessels will be faced with new problems. For example, should some of the evacuees be sent to the deck, waiting for rescue? Based on which criteria can decide who should go to the lifeboats and who should go to the deck and wait for rescue? These questions are obviously beyond the scope of this thesis. Hence, in the modelling in this thesis, the lack of capacity of lifeboats is not considered, and an assumption is made that the full capacity of all the lifeboats is no smaller than the number of evacuees on board.

With regard to the direction of an edge, there are three categories of network graphs, namely directed, undirected and mixed. In a directed graph, each edge carries an orientation, usually indicated by directed arrows each edge in the network, while in an undirected graph, the edges between paired nodes are unordered. The third kind of graphs are called mixed networks, where some edges are directed but some are not (Ford & Fulkerson, 1962). In the case in this thesis, definitely an undirected network should be built for the cruise vessel layout, because the corridors and stairways on cruise vessels can be passed in both directions. In addition, the direction of flow within an edge can also change over time, and it is also possible that sometimes opposite flows exit in one edge at a same time. Therefore, there's no reason to assign the directions of edges in the network of interest in this thesis, and the graph of network established in previous contents should be undirected.

However, it is a vital problem about how to handle opposite flows within one edge at the same time. As mentioned in the previous paragraph, it is likely that we have opposite flows within one edge at the same time, and this is mainly because that, some edges are not accessible for disabled evacuees and therefore they might be guided to a take a detour, and some parts of the detour route could be opposite to the direction of the main flow at that time. Furthermore, in reality, not everybody follows the instructions, and things are unlikely go exactly the same as calculated in the simulation. Still, the opposite flow problem could be even more complicated if sending crews to recue those who are difficult to move or who get trapped is taken into consideration. For these reasons, the opposite flow problem is actually somewhat inevitable during the evacuation on a cruise ship. In order to model this problem, there are several questions that need to be considered, and therefore it is difficult to model the problem of opposite flows. For example, should the two opposite flows share the same capacity of the edge? What is the influence of opposite flows on the speed of the evacuees? Certainly, opposite flows during an emergency evacuation process can also lead to congestions, and even worse, stampede accidents. However, the problem of opposite flow will not be modelled and simulated in this thesis, because generally, the directions of the majority of evacuees in the same node are identical, excepting for wheelchair users who are likely to detour. Since there are only 5 wheelchair users among 100 evacuees, the possible influence from the opposite flow problem is supposed to of minor importance.

6.1.3. Input Data of Hazard

The time span of the whole evacuation is set to 500 seconds, and the iteration frequency is of each one second. However, the high frequency of iteration is infeasible to giant vessels in real cases, and also brings huge burden to the computation. Because in this thesis, the simulation is implemented for a relatively small illustrative example, and the number of evacuees involved is only 100, not very large, frequent iteration of each second is adopted. But if the model can be expanded to large vessels, the iteration frequency should be lower to a reasonable extent.

The next step is to add the data of a fire disaster. In this simulation, it is assumed that, when t=0, a fire is detected at node 4, and the emergency evacuation starts. When t=30, the fire bursts out from node 4, and the edge (4,6) and (3,4) are marked as out of use after t=30. At t=60, the fire spreads to node 3, and the edges connecting to node 3 are therefore out of use. Similarly, the fire spreads to node 5 at t=100, to node 2 at t=120, to node 6 at t=150, to node 7 at t=200, to node 8 and 14 at t=240, to node 1 and 12 at t=280, to node 13 and 24 at t=300, to node 18 and 19 at t=350, to node 15 and 16 at t=420, to node 9, 22 and 25 at t=450, and to node 11, 20 and 34 at t=480. In addition, after t=30, the elevator, which is represented by edge (13,34) is out of use due to the burning of wires.

In this simulation, the development of a fire disaster on board is assumed beforehand, without any uncertainty, and the information is pretended as updating over time during the simulation, and the route suggestion is correspondingly adjusted according to that. The spread speed and direction of fire are based on reasonable assumptions, but these assumptions actually lack the support of relevant research and theory. Moreover, in reality, the development of fire disaster on board is actually stochastic. In a stochastic setting, there should be multiple fire spreading scenarios with different probabilities. But in this thesis, solely one specific fire spreading scenario is adopted with 100% probability. Therefore, for the decision-makers, the future development of the fire is surely uncertain, but the typical setting of the scenario does not consider the stochastics of the fire disaster development.

Another problem is that, as discussed at the end of Section 5, the proposed model does not really solve the uncertainty. The evacuation decisions are made based on available information, which is updated over time. However, if a stochastic setting is adopted, the timing of an edge to be blocked due to the fire is also stochastic. For example, there is a chance of 50% that an edge is going to be ruined by the fire in 30 seconds, and 50% in 40 seconds, then should any evacuees be guided to that edge at present? Which evacuees should be sent to that edge, probably the youngsters rather than the elder.

6.1.4. Route Decision and Evacuees Guiding

With the network constructed and the evacuees initiated, step 4 is then executed, the equivalent length of each edge is calculated for the time t=0. Next comes to step 5, with the equivalent lengths at t=0 available, the Dijkstra algorithm is used to determine the shortest route from each source node to each sink node. For each source node, there are four options of sink node, and the distance to which is shortest is set as the target sink, and the route passing which nodes and edges are then generated. However, in this model, only the next edge or next node to go is of interest. Because in practice, the evacuees who are escaping only want to know which way to go when they are facing an intersection of corridor. In addition, because this model is a time period rotated model, and step 4 and step 5 will be iterated each second according to the updated information, according to which the optimal route can change over time. For these reasons, during each iteration, for each source node, only the next sink or edge to go is extracted and registered, and all the evacuees at that node at that time will be guided to the next place according to that. Certainly, the wheelchair users are likely to be guided to a different way from other evacuees, because some edges are inapplicable to them. The same steps are iterated every second, and the instruction at each node is possible to change due to the updated information over time.

After the next place to go is decided, the travel time is then calculated with Equation 2 in Section 5.1, for three groups of evacuees, according to their different speeds. The base speed is determined by the speed function of density, which is Equation 3 in Section 5.1. After one evacuee arrives at the new node, for example, at time t=8, then this evacuee will go to next node at t=9 as the model suggests, which is generated by the iteration at time t=9. During t=1 to t=8, no new directions are given to this evacuee, until t=9 he or she finishes the previous edge travel. The direction at one node at one specific time might varies according to different evacuee groups.

When an evacuee arrives the target sink, his or her evacuation is then finished, and the available capacity of lifeboat he or she gets on is reduced correspondingly. After the capacity of one lifeboat becomes zero, the representative sink is moved from the sink set, and afterwards no evacuees will be guided to there.

6.2. Simulation Result Analysis

6.2.1. Necessity of Real-time Guiding

In order to evaluate the importance of guiding, holding other things equal, the evacuation with and without guiding are firstly compared. The process of evacuation with guiding is as explained in previous sections. For evacuations without guiding, it is assumed that all the evacuees pick the route according to their own judgement. For instance, passengers try to escape with the nearest exit they memorized, such as the recommended evacuation route during the drill upon boarding, or the evacuation route pasted behind the cabin door. Actually, the behaviour of evacuees is stochastic, no matter guiding is offered or not, and the uncertain evacuees behaviour is discussed in detail in Section 7.1. The uncertainty of evacuees behaviours should be involved in the modelling and simulation. But in this thesis, the stochastic evacuees behaviours are not considered, and it is assumed that, all the evacuees strictly follow the instructions if guiding is offered. Without guiding, the evacuees are assumed to evacuate with the shortest route in the physical length.

The result is that, without guiding, there are 87 evacuees out of 100 managed to escape, within 500 seconds. However, the figure rises to 90 if proper guiding is offered during the evacuation. In addition, for those who successfully evacuated, the average evacuation durations are 124 and 133 seconds, in the case of simulation with and without guiding, respectively. Therefore, with the typical settings in this scenario, from the angle of the whole system optimum, evacuation with guiding can help more evacuees to escape from the emergency fire disaster, and can also effectively cut down the average evacuation time by 9 seconds.

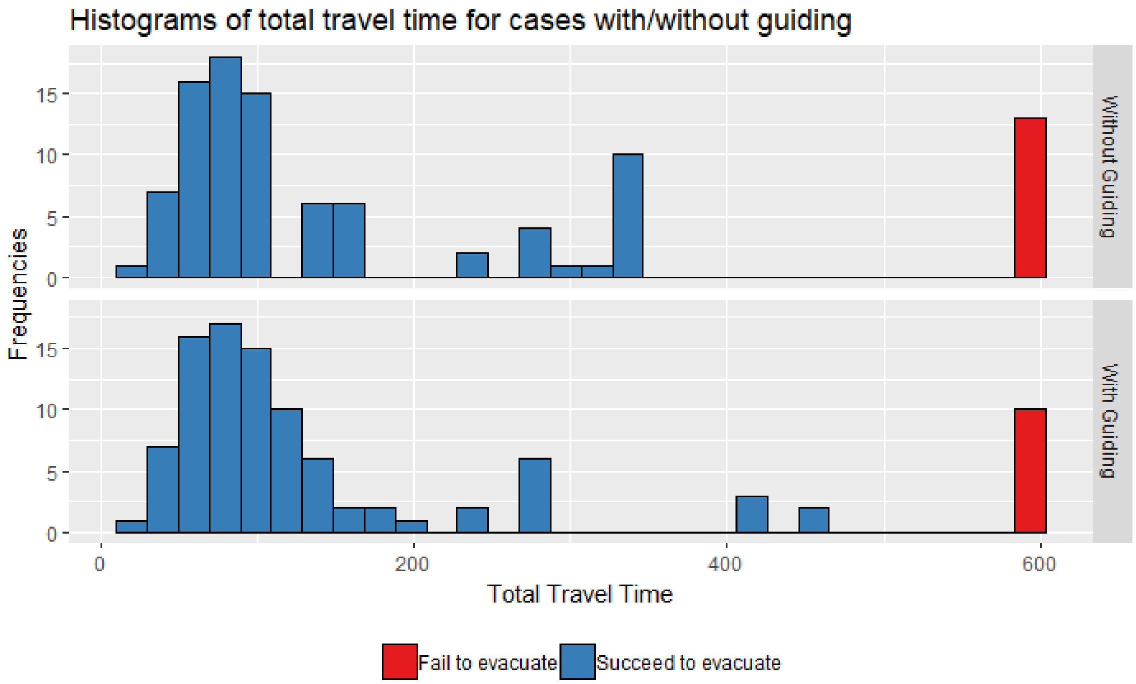

Figure 3: Distributions of evacuation time for cases with/without guiding

In Figure 3 shows the distributions of total evacuation time for those who managed to escape, in both evacuation simulations with and without guiding. In addition, the number of evacuees failed to evacuate is also demonstrated in this figure. As demonstrated in Figure 3, all the blue strips represent the numbers of evacuees managed to escape, with their evacuation time falling into the corresponding time intervals, while the two red strips represent the numbers of evacuees who failed to escape in both cases. In both cases, the majority of total travel time concentrates in the interval from 60 to 120 seconds, and both the distributions are obviously right skewed, and have a relatively long tail. These features indicate that, for the evacuees who managed to escape, the distribution of their evacuation time is similar. Although the majority of them have a relatively short evacuation time, roughly less than 150 seconds, there are still a few evacuees with long evacuation time, which cannot be revealed solely by the average evacuation time. In addition, from the two red strips, which represent the number of evacuees failed to escape, 13 evacuees got trapped without guiding, but 3 of them could be able to get out if following proper guides. Obviously, an evacuation model with guiding helps avoid the evacuees from getting stuck.

Next, the evacuation process of those three evacuees who could have escaped successfully if with guiding are studied. The three evacuees are initially at node 19. Under the circumstance of no guiding, those three evacuees decided the route by themselves, that is, use the elevators, which is represented by the edge (13,34) in the graph. However, the elevator shuts down at t=30 according to the assumed disaster scenario, and all the three people are stuck. However, if the evacuation is appropriately guided, and if all the evacuees strictly follow the instructions, those three evacuees are supposed to be guided to another direction, and finally manage to escape.

To sum up this section, based on the assumed event and scenario in the simulation, the evacuation with guiding outperforms that without guiding. From the system level, the total number of evacuees who successful escaped is increased by 3, or 3% if with appropriate guiding, and the average evacuation time is also deducted by 9 seconds, or 7% in percentage. From the individual aspect, if being strictly complied with, proper guiding during evacuation can prevent the evacuees entering dangerous zone based on their own experience or judgement, or not knowing the updating hazardous information. Hence, proper guiding is necessary in evacuations on cruise ships during a fire emergency.

6.2.2. Necessity of Looking Into the Future

Another finding from the simulation is the strong necessity of looking one step ahead of time and considering time-dependent prediction of disaster development when suggesting the next step to go for the passengers during an emergency evacuation.

From the result of the simulation case of a guided evacuation, it is easy to find out that, for the evacuees (except for wheelchair users) who are located at a same node at a same time, usually the same evacuation route is suggested for all of them. However, sometimes, only the young people managed to pass a certain evacuation path, but the remained elder people with a relatively low walking speed failed and got stuck in a certain edge. For instance, evacuee No. 5, 44 and 45 are all initialized at node 6, and evacuee No. 5 is a young person while No. 44 and 45 are elder people. The evacuation path for evacuee No. 5 is:

$$6 \xrightarrow{25} 4 \xrightarrow{13} 3 \xrightarrow{32} 24 \xrightarrow{23} 23 \xrightarrow{23} 24 \xrightarrow{10} 25 \xrightarrow{13} 26 \xrightarrow{9} 30 \xrightarrow{38} 31 \xrightarrow{13} 44\,,$$

and the evacuation path for evacuee No. 44 and 45 is:

$$6 \xrightarrow{32} 4 \nrightarrow 3\,.$$

where $u \xrightarrow{TT(u,v)} v$ means the evacuation path from node u to node v, taking the travel time of $TT(u,v)$, and $u \nrightarrow v$ means getting stuck at edge (u,v).

Another example is with evacuee No. 6, 7, 50, 51, 52 and 53, who are all initialized at node 8. Evacuee No. 6 and 7 are young people with high walking speed, and No. 50, 51, 52 and 53 are elder people with relatively low speed. Evacuee No. 6 and 7 have a node route:

$$8 \xrightarrow{17} 7 \xrightarrow{30} 5 \xrightarrow{9} 3 \xrightarrow{32} 24 \xrightarrow{10} 25 \xrightarrow{34} 35 \xrightarrow{13} 36 \xrightarrow{9} 39 \xrightarrow{62} 38 \xrightarrow{13} 42\,,$$

and successfully escaped. However, evacuee No. 50, 51, 52 and 53 are guided to a route:

$$8 \xrightarrow{21} 7 \xrightarrow{37} 5 \xrightarrow{11} 3 \nrightarrow 5$$

but finally got stuck at the edge (3,5).

These two examples both indicate the importance of looking one step ahead of time. In other words, considering time-dependent prediction of disaster development when suggesting a next direction for evacuees. In the first example, at the time t=0, it is node 4 the next node to go with the shortest equivalent length. However, for young people, it only takes 25 seconds to pass the edge (6,4), while for elder people, it takes 32 seconds. According to the fire spread scenario described in Section 6.1.3, it would be safe to enter the edge (3,4) no later than t=30, because the fire is assumed to burst out from node 4 at t=30, leading to the edge (3,4) being blocked. Obviously, if the future spread of fire disaster is taken into consideration, the elder people should not be guided from node 6 to node 4, and probably taking a detour is a safer choice for them. Similarly, in the second example, the elder passengers are guided from node 5 to node 3 at the time t=59, according to the shortest path determination method using Dijkstra algorithm. While after getting to node 3, the evacuees are told to go back to node 5 but they finally get trapped in that edge, because of the quick spread of fire. The fire will spread to node 3 connecting edges at t=60, according to the fire scenario assumption in Section 6.1.3. If look one step ahead of time, upon arrival at node 5, at t=58, the evacuee No. 50, 51, 52 and 53 should be guided back to node 7 or 14 immediately, instead of going to node 3, which will be burnt up in 2 seconds.

Therefore, looking one step ahead and taking the influence of disaster on the future evacuation path is important, and with which some wrong decisions could be avoided. Hence, the model can be adjusted to include additional steps of evaluating the future availability of paths according to the predictable hazardous situation. The adjusted model is of the following steps:

Step 1: Translate the cruise vessel layout into a graph G of network, with vertices V and edges E. Input the parameters of each edge, including physical length and width, type of facility and availability. The location and capacity of each sink node (lifeboat in this case).

Step 2: Input the data of evacuees. For example, which category the evacuee belongs to, and the initial locations of them.

Step 3: Input the data of fire disaster situation over time. For example, when and where the fire is spread to, causing which edges become out of use. In addition, use the “predicted data” of fire to calculate the “safe time” of each edge in the network.

Step 4: Calculate the equivalent length of each edge over time with Equation 6.

Step 5: Call Dijkstra algorithm to determine the shortest routes from each source node to each sink node, among which the shortest one is picked. Then with this shortest route, the next edge or node to go is extracted, with which the evacuees are guided when arriving that typical source node at that time.

Step 6: According to the next instruction generated by step 5, look another step ahead (further next step), to see whether the further next step is safe upon arrival to it. This can be realized by comparing the safe time of the next node to the time of arrival to it. If the further next step will be unsafe upon arrival, another instruction will be generated by updating the information and rerunning step 5.

Step 7: Update the data in step 1 and step 2 over time, and based on which iterate step 4, step 5 and step 6 as frequently as possible. The location of each evacuee should also be adjusted according to the instant data from the evacuees tracking system.

The underlined parts in the above steps of modelling are the newly-added adjustments of thinking availability of future paths. This thinking is actually an attempt to capture the future uncertainty of the fire development. But in the specific setting in this thesis, the fire development is totally predictable, because of non-consideration of the stochastics of fire spread. In step 3, additional “safe time” is calculated, according to the of fire spread scenario stated in Section 6.1.3. For example, at t=30 the fire bursts out from node 4 and the edge (4,6) and (3,4) are marked as out of use after t=30. For this reason, the safe time should be 30 seconds for edge (4,6) and (3,4). For this reason, in the original guiding case, the evacuation path for evacuee No. 44 and 45 is:

$$6 \xrightarrow{32} 4 \nrightarrow 3\,,$$

where the arrival time at node 4 is t=31, and the supposed departure time from node 4 to node 3 is at t=32. According to the procedure in step 6, by comparing the arrival time and the safe time of next node, which is node 4 in this example, it becomes unsafe and inaccessible at t=30, while the evacuees No. 44 and 45 are supposed to enter the edge (3,4) at t=32. Therefore, by looking one step ahead, the instruction for the evacuees No. 44 and 45 to travel from node 6 to node 4 is inappropriate. In the updated version of evacuation guiding simulation, the evacuation route for the evacuees No. 44 and 45 is:

$$6 \xrightarrow{16} 7 \xrightarrow{37} 5 \xrightarrow{74} 14 \xrightarrow{32} 15 \xrightarrow{11} 16 \xrightarrow{27} 17 \xrightarrow{40} 37 \xrightarrow{42} 31 \xrightarrow{42} 37 \xrightarrow{11} 40 \xrightarrow{53} 39 \xrightarrow{44} 38 \xrightarrow{16} 42\,,$$

where another instruction of guiding from node 6 is adopted and the two evacuees are able to escape. Furthermore, similar for evacuee No. 50, 51, 52 and 53, who are not able to evacuate in the original evacuation guiding simulation also successfully escape in the future looking guiding version.

As visualized in Figure 4, the simulation result of the guiding model with future looking is that, out of the total 100 evacuees, 96 of them managed to escape, 6 more than the number in the original guiding version, and the success rate increases by 6%. The remaining four evacuees are evacuee No. 96, 97, 98 and 99, who are all wheelchair users and initialized at deck 4. They are not able to go downstairs after t=30 because the only elevator (13,34) is out of use after t=30, according to the disaster scenario stated in 6.1.3.

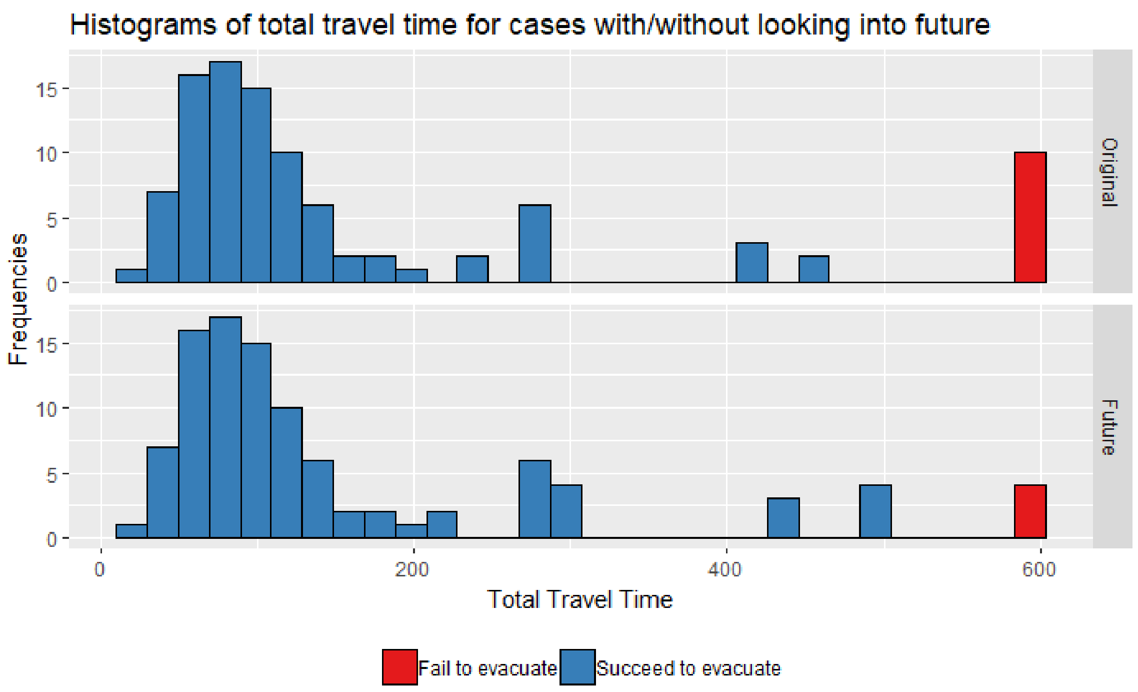

Figure 4: Distributions of evacuation time for cases with/without future looking

However, for the evacuees who managed to escape, the average evacuation time is 140 seconds, 7 seconds longer than that in original guiding evacuation simulation. To deeper understand this phenomenon, the route of each evacuee in the simulation result of future looking evacuation guiding model is studied, and there is a problem of turning back in the routes of several evacuees. The first occurrence of turning back is in the route of evacuee No. 5, and the route is:

$$6 \xrightarrow{25} 4 \xrightarrow{13} 3 \xrightarrow{32} {\color{red}24 \xrightarrow{23} 23 \xrightarrow{23} 24} \xrightarrow{10} 25 \xrightarrow{13} 26 \xrightarrow{9} 30 \xrightarrow{38} 31 \xrightarrow{13} 44\,,$$

where the part marked red represents the turning back problem involving in this route. The evacuee No.5 goes from node 24 to 23 at first, but turns back from 23 to 24 immediately. The primary intension for evacuee No. 5 is to go from node 23 to node 41, which is a sink node. However, when the evacuee is on the way from node 24 to 23, the capacity of node 41 becomes full. Unlike the disaster situation, the capacity of sink nodes is hard to predict in advance, and in this example, it is inevitable for evacuee No. 5 to turn back from node 23 due to insufficient available capacity in the original target sink.

On the other hand, the problem of turning back can also be caused by inadequate consideration of disaster development prediction. For example, this kind of turning back occurs in the route of evacuee No. 50, 51, 52 and 53, and the route is:

$$8 \xrightarrow{21} 7 \xrightarrow{37} 5 \xrightarrow{21} 7 \xrightarrow{21} 8 \xrightarrow{42} 16 \xrightarrow{11} 15 \xrightarrow{16} 20 \xrightarrow{24} 39 \xrightarrow{78} 38 \xrightarrow{29} 42\,,$$

where the turning back part in the route is also marked red. If only look one step ahead of time, the path suggestion of $8 \xrightarrow{21} 7 \xrightarrow{37} 5$ is no problem, because it takes 58 seconds to travel from node 8 to 5, and is within the safe time of node 5, which is 100 seconds. Then, the original attempt is to go to node 3 upon arrival at node 5, that is, $8 \xrightarrow{21} 7 \xrightarrow{37} 5 \rightarrow 3$. According to the rule of future looking evacuation guiding, when the evacuee is at node 7, t=20, and next step is 5, which will take 37 seconds to reach, and therefore, the predicted time to arrive node 5 is when t=57. Looking one step ahead, the further next node after node 5 is node 3, which will be safe until t=60, which is later than t=57. For this reason, no problem to have a recommended route $8 \xrightarrow{21} 7 \xrightarrow{37} 5 \rightarrow 3$. However, after arriving at node 5, and another beforehand check of next step after node 3 is conducted, which should be node 24 with safe time before t=60. Therefore, only if $8 \xrightarrow{21} 7 \xrightarrow{37} 5 \xrightarrow{<2} 3 \rightarrow 24$, this route is feasible, that is, getting to node 24 before t=60, and in that way, the time spending from node 5 to node 3 should be no more than 2 seconds, which is impossible. Based on this judgement, a turning back direction is made. This kind of turning back is possible to be avoided if enough future steps are taken into consideration beforehand.

However, it should be clarified that, turning back is always an option for evacuees in a reality or in a stochastic setting. But, turning back based on the setting of scenario in this thesis is totally avoidable, if more steps ahead of time are taken into consideration. Nevertheless, looking more steps ahead of time is at a cost of computation efficiency, and it is also hard to say exactly how many steps into the future is enough to completely avoid turning back problems. This is actually one of the weakness of the model proposed.

On the other hand, although the turning back due to inadequate consideration of predicable fire disaster development is too costly to solve in the model, the turning back problem due to a sudden short of capacity of the target sink can be avoided to a certain degree. The method is to add extra penalty to the edges leading to the sink nodes when calculating the equivalent lengths for these edges, according to their available capacities over time.

6.2.3. Possible Rerouting Based on Sink Capacity Monitoring

As discussed at the end of the previous section, in an attempt to avoid the turning back problem caused by a sudden shortage of capacity of the target sink, an extra penalty term on the available capacity of sink nodes is added when calculating the equivalent length. For example, if the available capacity of one sink node is below 10%, a large penalty would be added to the edge connecting to this sink node, thus making the path leading to this sink "longer" and avoiding guiding too many evacuees to this sink.

The updated formula to calculate the equivalent length of an edge becomes:

$$\begin{aligned} L(u,v)_t = l(u,v)\,(1 + \varpi_p D(u,v)_t + \varpi_o b_o(u,v)_t + \varpi_s b_s(u,v) \\ + \varpi_n b_s b_n(u,v) + \varpi_e (1 - b_z) b_e(u,v) + \varpi_c b_l(u,v)) \end{aligned} \tag{8}$$

The red marked term is the newly added penalty term on sink capacities, where $b_l(u,v)$ is a binary parameter to tell whether the edge (u,v) is an edge leading to a sink node. $b_l(u,v) = 1$ if the edge (u,v) is a sink-linking edge, and 0 otherwise. ϖ_c is the penalty coefficient associated to the available capacity percentage of a sink, and is generated by a customized penalty function, which is as demonstrated in Equation 9:

$$\begin{array}{ll} \varpi_c = 99 & ac = 0 \\ \varpi_c = 10 & 0 < ac \leqslant 10\% \\ \varpi_c = 8 & 10\% < ac \leqslant 20\% \\ \varpi_c = 5 & 20\% < ac \leqslant 30\% \\ \varpi_c = 3 & 30\% < ac \leqslant 50\% \\ \varpi_c = 2 & 50\% < ac \leqslant 60\% \\ \varpi_c = 1 & 60\% < ac \leqslant 80\% \\ \varpi_c = 0 & 80\% < ac \leqslant 100\% \end{array} \tag{9}$$

In Equation 9, ac is the percentage of available capacity of a sink. The basic idea is that, if ac is 0, then an enough large penalty coefficient is assigned, namely 99 in this formula.

If ac is larger than 80%, then no penalty adding, and the coefficient is 0. With the available capacity percentage lower, a bigger penalty coefficient is assigned. The penalty function of ϖ_c in Equation 9 is based on reasonable assumption.

After implementing the updated equivalent length formula Equation 8, the simulation result indicates that, the problem of turning back caused by a sudden shortage of capacity of the target sink is avoided. In addition, the average evacuation time for those who successfully escaped drops from 140 to 124 seconds. Furthermore, as demonstrated in Figure 5, there are fewer outliers in the result of simulation based on updated model considering capacity availability. Additionally, for those who managed to evacuate, the clearance time of the simulation of model considering capacity availability is around 360 seconds, while in the case of not considering capacity availability, the clearance time is around 500 seconds.

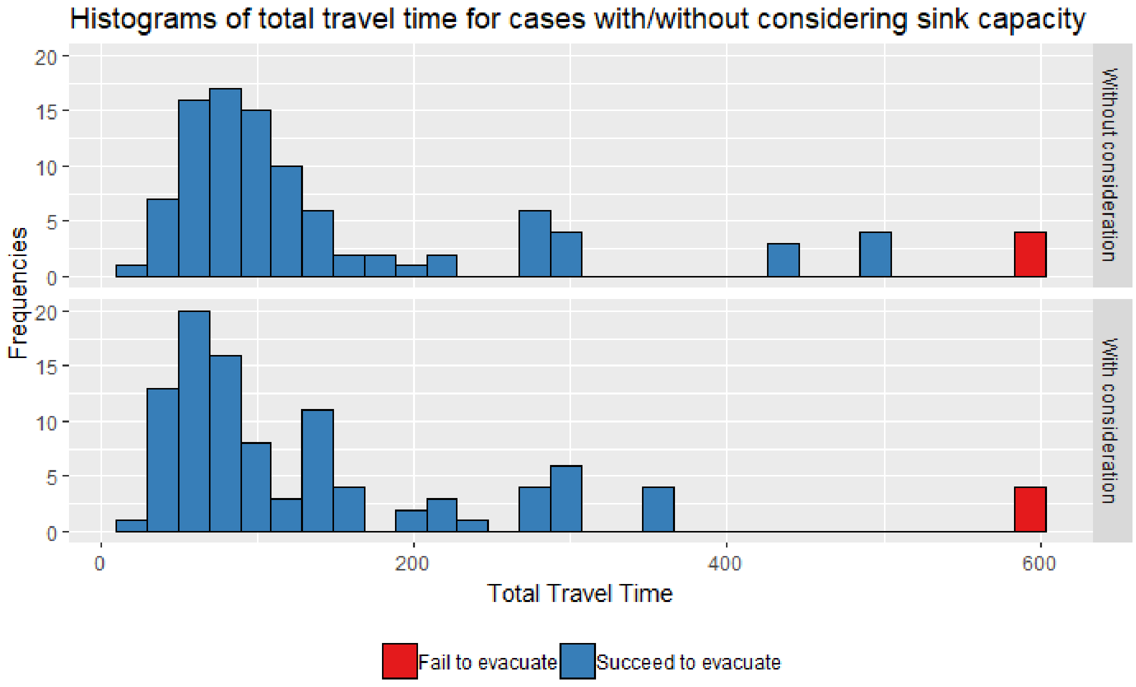

Figure 5: Distributions of evacuation time for cases with/without considering sink capacity

6.3. Summary of Simulation Results

Table 6: Summary of simulation results with different models

Type of model to simulate	Number of evacuated passengers	Average evacuation time (s)
Without guiding	87	133
With guiding	90	124
With guiding with consideration of future step	96	140
With guiding with consideration of future step and sink capacity availability	96	124

To sum up the learning process of the simulation section, in general, four simulations of four different models were conducted and the original model were updated twice according to the simulation results. The two main indicators of interest are the number of evacuated passengers and the average evacuation time of them, and the results are listed in Table 6. The distribution of total evacuation time is also observed and analysed.

Firstly, the evacuation model with and without guiding was simulated and the results were compared. It is obvious that the model with guiding outperforms the one without guiding, because without guiding, it is possible that a certain proportion of passengers get trapped based on their own judgement, without knowing the current information of how fire is spreading. However, the evacuation model with guiding takes the development of hazard into consideration, thus avoiding the trapping cases that could be avoided in the model without guiding.

Next, specific to the evacuation model with guiding, a new problem was detected. If only focus on the next place to go at each node based on the shortest route determined by the Dijkstra algorithm, some evacuees are likely to get trapped because when they arrive at the next node, the originally attempted route has been blocked by the disaster. Moreover, it is always a situation that, an identical route is suggested for both young people and aged people located at a same place at a same time. However, the youngsters can pass but the elders get stuck, because the walking speed of elder passengers are lower than that of youngsters. For this reason, the first update applied to the original evacuation guiding model is to look one step ahead of time, and consider time-dependent validation of each route under the assumed fire spread scenario. This update is a primary attempt to acquire the future uncertainty. The effect of the update is as demonstrated in Table 6, that 6 more evacuees managed to escape. However, the average evacuation time increased. After an examination on the simulation results, another problem was detected.

The other problem is about turning back. There are two reasons for turning back problems, one is the inadequate consideration of predictable disaster developments, in brief, sometimes looking only one step ahead of time is not enough. The other one is a sudden shortage of sink capacity. The turning back due to the former reason is difficult to solve, because it is hard to say exactly how many steps ahead is adequate to totally avoid turning back, and also looking more steps ahead of time actually adds burden to model computations, and therefore lower iteration frequency could be combined with more steps looking ahead of time. However, the turning back problem caused by the latter reason, that is, insufficient sink capacity, is possible to solve. The reason why some evacuees have to turn back when they are approaching the target sink is that too many evacuees are guided to that sink at the same time, which exceeds the remaining capacity of it. Hence, by adding additional penalty on edges connecting to a sink, which is about to be fully loaded, is a possible solution to this kind of turning back problem. This is the second update to the original evacuation guiding model, and the result is listed in Table 6, where the average evacuation time is cut to 124 seconds from the previous 140 seconds. In addition, according to the detailed discussion in precious section, the outliers in the most updated version is also reduced, therefore, the whole system optimum is better achieved after the latest update.

Finally, the four evacuees who never escaped cannot be ignored. It is a realistic problem with the movability of wheelchair users during emergencies. It is always the case that the elevators is the only option for disabled people to get downstairs or upstairs, but elevators can be out of use during emergencies. Therefore, specific rescue schemes are urged to be made for disabled passengers on cruise ships, and also the barrier-free facilities accessible under emergencies should be considered more in the designing stage of new cruise vessels.

7. Discussion

7.1. Limitations

Firstly, an obvious weakness of the proposed model is the inevitable problem of turning back due to inadequate consideration of predictable disaster development, with the typical setting of the single scenario in this thesis. As is also discussed in the previous section, this problem can be addressed only by looking enough steps ahead of time, which is not only negative to computation efficiency, but also infeasible because of the difficulty to capture all the influence factors to the edge equivalent length over time.

Secondly, the proposed model does not consider the potential opposite flow problem. For simplification, it is assumed that there is no influence from opposite flows in an edge at the same time, on the edge capacity assignment and flow moving speed. But this assumption is obviously problematic.

Thirdly, the considerable potential influence of wheelchairs is underestimated. Especially in a narrow corridor or at a doorway, the existence of a wheelchair is similar to a slow-moving barrier for other evacuees. Therefore, in the current version of proposed model, the calculation of travel time failed to capture the negative influence of wheelchair blocking.

Moreover, for simplification, the proposed model does not consider any psychological behaviours of evacuees. Firstly, it was assumed that all the evacuees strictly follow the instructions generating by the model, but such assumption is too idealized. In reality, there could be certain percentage of evacuees do not totally follow the instructions, for instance, when the route suggested is opposite to their subjective judgements and feelings. Moreover, the families of a wheelchair user could rather choose to follow the detoured route suggested for the wheelchair group, instead of evacuating separately. Furthermore, it is also unwise to separate a child from his or her parents when assigning lifeboats. For these reasons, the failure to involve the psychological factors and group behaviours in the model could make the model too idealized and unrealistic.

Additionally, the proposed model does not include some of the cruise specific features that affect evacuations. For instance, the influence on evacuees walking speed on ships during fierce shakes in storm; the influence on evacuees walking speed on ships during heeling and sinking; the influence on the release of lifeboats during severe heeling of ships.

Furthermore, the simulation is only with one scenario in a single event. For this reason, the learning results from the simulation could have limitations. It is possible that there are potential problems with the models have not be discovered, due to the scarcity of scenarios and events applied to the simulation.

Another limitation from the simulation comes from the simplicity of example ship layout used for the simulation. It was difficult to get access to ship drawings, and the example ship layout is based on the deck layout pictures of “Oasis the Seas”, with all the parameters such as corridor length and width made up by assumptions. Therefore, not conducting the simulation based on real data of a ship may also have some influence on the simulation results.

On the other hand, the simulation in this thesis was conducted using R on a private laptop. For this reason, there is a limitation on the complexity of models to be simulated. If a professional ship simulator can be used, the efficiency and allowed complexity of model are both supposed to be improved.

Besides, in terms of the lifeboat capacity, in the simulation section, the total lifeboat capacity was set to the number exactly equals to the total number of evacuees. However, it could always be a case of insufficient lifeboat capacity, for example due to the fire disaster and possible heeling of ship, some lifeboats are actually out of use. In this case, a policy or a rule is needed to decide which passengers should be prioritised, and which ones should be guided to a relatively safe deck, waiting for rescue. The setting of such a rule is definitely out of the scope of this thesis, but once this kind of rule is available, the model should be expanded to take the problem of insufficient lifeboat capacity into consideration.

Finally, in the simulation conducted in this thesis, there is no occurrence of dense distributions of evacuees in a large area. For instance, think of the evacuee distribution in a big dining hall at meal time. It could be a problem that all the evacuees are guided to the nearest one or two lifeboats, whose capacity is far lower than the number of coming evacuees. Also, congestions is also a potential problem in this case.

7.2. Suggestions for Future Research

With reference to the above mentioned limitations, there are several suggestions for future research in different aspects. Firstly, suggestions regarding expanding cooperation and getting more resources. For example, try to cooperate with ship owners and thus getting access to ship drawings, which can improve the reliability of model simulations. Try to get access to a professional ship simulator as well, thus allowing the efficient simulation of future expanded model. If the professional ship simulator is accessible, the cruise specific influential factors, such as the periodic waves, fierce shaking of a ship during storm and the heeling and sinking of a ship, could be better simulated.

On the model level, for future research, the model should be expanded to include more details, such as the influence of wheelchair users on the speed of others, the cruise specific influential factors, the opposite flows problem, including the sending of rescue teams, the insufficient lifeboat capacity problem, psychological factors and group behaviours, and different kinds of evacuee distributions, involving extremely dense distribution cases. In addition, also consider other modelling method to determine the optimal evacuation route, trying to avoid inevitable weaknesses of the model.

For the simulation, multiple events with multiple scenarios should be adopted. In other words, update the model into a stochastic version, and study the gain from stochastic version compared to the current deterministic one.

8. Conclusion

Nowadays, cruising is becoming a more and more popular choice for tourists, and the number of cruising passengers has been growing rapidly. However, in recent years, several serious cruise ship disasters that cost numerous deaths and injuries have aroused the attention of the public. Therefore, it is urged to figure out an effective and robust way to guide the emergency evacuations on cruise vessels during the emergencies, under the technical barrier of data transfer on cruise vessels without cables, which could be burnt off during a fire emergency. The existing studies on the emergency evacuation specific for cruise vessels are rare, among which seldom have the researchers placed the emphasis on "guiding" the passengers, and the technical premise of wireless data communication on ships have almost never been considered.

Therefore, in this thesis, an implementable evacuation guiding model is proposed and simulated. The proposed model is able to guide the evacuees with the optimal route suggested over time for different groups of evacuees with different movability and speed, with consideration of the instant hazard development situation. The model is technically supported by the cutting-edge sensor mesh technology developed by ScanReach, with which the wireless data transfer in confined steel environments is feasible. The original version of the model has been updated twice according to the learning from the simulation results. The proposed model is implementable and the algorithms involved is simple enough to ensure the computation efficiency. But there are still some limitations with this model and are suggested as future research directions. Especially, the model does not solve the future uncertainty during the emergency evacuation on cruise vessels, and this is a major direction for future studies.

Furthermore, a major finding from the simulation is the scarcity of route choice for wheelchair users during emergencies. Therefore, specific rescue schemes are urged to be made for disabled passengers on cruise ships, and also the barrier-free facilities accessible under emergencies should be considered more in the designing stage of new cruise vessels.

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It is a challenging and time-consuming experience for me to work on this master thesis, but it is also a memorable and meaningful learning process. Especially when I managed to work out the model and code for the simulation, I was so excited, and I felt the fun of academic research for the first time.

At the end of this thesis, I would like to express my gratitude to my supervisor Stein W. Wallace, for suggesting me such an interesting and novel thesis topic, offering me incisive suggestions, and contacting the company with technical support as the premise of my whole methodology and modelling. I also appreciate the invaluable information I learned from the meeting with John Roger Nesje and Geir Todnem, the representatives of Scandinavian Reach Technology (ScanReach), who introduced and explained in detail about their unique sensor mech technology, which enables the research in this thesis be supported with the cutting-edge technology and thus implementable in real cases.

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Bergen, November 2019

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Meiqi Luo

References

A.J. King, S.W. Wallace, 2012. Modelling with Stochastic Programming. Springer Series in Operation Research and Financial Engineering.

A. Kimms, K.C. Maassen, 2011. Cell-transmission-based evacuation planning with rescue teams. J Heuristics (2012) 18:435–471.

C. Casareale, G. Bernardini, A. Bartolucci, F. Marincioni, M. D'Orazio, 2017. Cruise ships like buildings: Wayfinding solutions to improve emergency evacuation. BUILD SIMUL (2017) 10: 989–1003.

C.F. Daganzo, 1994. The cell transmission model: A simple dynamic representation of highway traffic consistent with hydrodynamic theory. Transpn. Res.-B. Vol. 28B, No. 4, pp. 269-287, 1994.

CLIA, 2018. 2019 Cruise Trend and Industry Outlook. Cruise Lines International Association.

D.R. Bish, H.D. Sherali, 2013. Aggregate-level demand management in evacuation planning. European Journal of Operational Research 224 (2013) 79-92.

E. Ronchi, P.A. Reneke, R.D. Peacock, 2014. A Method for the Analysis of Behavioural Uncertainty in Evacuation Modelling. Fire Technology, 50, 1545-1571, 2014.

E.W. Dijkstra, 1959. A Note on Two Problems on Connexion with Graphs. Numerische Mathematik 1, 269-271(1959).

F.L. Hitchcock, 1941. The distribution of a product from several sources to numerous localities. MIT Journal of Mathematics and Physics 20:224–230 MR0004469.

F. Muller, O. Wohak, A. Schadschneider, 2014. Study of influence of groups on evacuation dynamics using a cellular automaton model. Transportation Research Procedia 2 (2014) 169-176.

G.J. Lim, M.R. Baharnemati, S.J. Kim, 2015. An optimization approach for real time evacuation reroute planning. Ann Oper Res (2016) 238:375–388.

G.J. Lim, S. Zangeneh, M.R. Baharnemati, T. Assavapokee, 2012. European Journal of Operational Research 223 (2012) 234-245.

G. Zhang, D. Huang, G. Zhu, G. Huang, 2017. Probabilistic model for safe evacuation under the effect of uncertain factors in fire. Safety Science 93 (2017) 222-229.

HCM, 2010. Highway Capacity Manual. Transportation Research Board of the National Academies, Washington DC.

H.D. Sherali, 1982. Equivalent weights for lexicographic multi-objective programs: Characterizations and computations. European Journal of Operational Research 11 (1982) 367-379.

H.D. Sherali, A.L. Soyster, 1983. Preemptive and Nonpreemptive Multi-Objective Programming: Relationships and Counterexamples. Journal of Optimization Theory and Applications: Vol. 39, No.2, February 1983.

H. Kim, M. Roh, S. Han, 2019. Passenger evacuation simulation considering the heeling angle change during sinking. International Journal of Naval Architecture and Ocean Engineering 11 (2019) 329-343. Maritime Injury Guide, 2018. Cruise Ship Safety Statistics. <https://www.maritimeinjuryguide.org/blog/cruise-ship-safety-statistics/>, viewed 6 Sep, 2019.

H. Liu, X. Luo, 2012. Optimal evacuation routes on cruise ship in fire based on equivalent length. Journal of Shanghai Maritime University, 33(1), p 32.

IMO, 2013. IMO-What it is. International Maritime Organization.

IMO, 2016. MSC.1/Circ.1533. Revised Guidelines on Evacuation Analysis for new and existing Passenger ships. International Maritime Organization.

J.A. Capote, D. Alvear, O. Abreu, A. Cuesta, V. Alonso, 2012. A Stochastic Approach for Simulating Human Behaviour During Evacuation Process in Passenger Trains. Fire Technology, 48, 911-925, 2012.

J. Chen, J. Ma, S. Lo, 2016. Modelling Pedestrian Evacuation Movement on a Swaying Ship. Traffic and Granular Flow ’15, DOI 10.1007/978-3-319-33482-0_38.

J.G. Wardrop, 1952. Road paper: Some theoretical aspects of road traffic research. ICE Proceeding: Engineering Divisions, Ice Virtual Library, Vol. 1, 1952, pp. 325-362.

J. Li, H. Zhu, 2018. A Risk-based Model of Evacuation Route Optimization under Fire. 2017 8th International Conference on Fire Science and Fire Protection Engineering. Procedia Engineering 211 (2018) 365-371.

J. Li, K. Ozbay, 2015. Evacuation Planning with Endogenous Transportation Network Degradations A Stochastic Cell-Based Model and Solution Procedure. Netw Spat Econ (2015) 15: 677-696.

J. Zhang, Y. Liu, Y. Zhao, T. Deng, 2018. Emergency evacuation problem for a multi-source and multi-destination transportation network mathematical model and case study. Annals of Operations Research, https://doi.org/10.1007/s10479-018-3102-x, published online: 06 December, 2018.

L. Ford, D. Fulkerson, 1962. Flows in networks. Princeton University Press, Princeton, NJ, USA.

L. Fu, J. Fang, S. Cao, S. Lo, 2018. A Cellular Automaton Model for Exit Selection Behaviour Simulation during Evacuation Processes. Procedia Engineering 211 (2018) 169-175.

L. Han, 2007. What is an effective evacuation operation? J. Urban Plann. Dev. 133(1) (2007) 3-8.

L. Wang, L. Yang, Z. Gao, S. Li, X. Zhou, 2016. Evacuation planning for disaster responses: A stochastic programming framework. Transportation Research Part C 69 (2016) 150-172.

M. Cisek, M. Kapalka, 2014. Evacuation Route Assessment Model for Optimization of Evacuation in Buildings with Active Dynamic Signage System. Transportation Research Procedia 2 (2014) 541-549.

Maritime Injury Guide, 2018. Cruise Ship Safety Statistics. <https://www.maritimeinjuryguide.org/blog/cruise-ship-safety-statistics/>. Viewed on 16 November, 2019.

M.J. Alam, M.A. Habib, 2019. Mass Evacuation of Halifax Canada: A Dynamic Traffic Microsimulation Modelling Approach. Procedia Computer Science 151 (2019) 535-542.

M.S. Abdalzaher, H.A. Elsayed, 2019. Employing data communication networks for managing safer evacuation during earthquake disaster. Simulation Modelling Practice and Theroy 94 (2019) 379-394.

O. Jahn, R.H. Mohring, A.S. Schlz, N.E. Stier-Moses, 2005. System-optimal routing of traffic flow with user constraints in networks with congestion. Oper. Res. 53(4) (2005) 600-616.

P. Duan , S. Xiong , C. Yang, H. Zhang, M. Liu, 2016. Personalized route planning system based on Wardrop Equilibrium model for pedestrian–vehicle mixed evacuation in campus. Journal of information security and applications 31 (2016) 14-22.

P. Ghasemi, K.K Damghani, A. Hafezalkotob, S. Raissi, 2019. Uncertain multi-objective multi-commodity multi-period multi-vehicle location-allocation model for earthquake evacuation planning. Applied Mathematics and Computation 350 (2019) 105-132.

P.L. Yu, 1975. Domination Structures and Nondominated Solutions, Multi-Criteria Decision Making, Edited by G. Leitman and A. Marzollo. Springer-Verlag, Berlin, Germany, 1975.

S. Aalami, L. Kattan, 2018. Fair dynamic resource allocation in transit-based evacuation planning. Transportation Research Part C 94 (2018) 307-322.

S. Karabuk, H. Manzour, 2019. A multi-stage stochastic program for evacuation management under tornado track uncertainty. Transportation Research Part E 124 (2019) 128-151.

S.W. Wallace, 2005. Decision making under uncertainty: The art of modelling. NHH Norwegian School of Economics, Norway.

V. Bayram, 2016. Optimization models for large scale network evacuation planning and management: A literature review. Surveys in Operations Research and Management Science 21 (2016) 63-84.

W. Zhu, H. Ding, T. Wang, 2009. The application of fire spread and evacuation simulation technology in large stadium. Stoch Environ Res Risk Assess (2009) 23: 433-439.

X. Zhang, G. Chang, 2014. A dynamic evacuation model for pedestrian–vehicle mixed-flow networks. Transportation Research Part C 40 (2014) 75-92.

Y. Li, M. Chen, Z. Dou, X. Zheng, Y. Cheng, 2019. A review of cellular automata models for crowd evacuation. Pysica A 526 (2019) 120752.

Y. Shin, S. Kim, I. Moon, 2019. Simultaneous evacuation and entrance planning in complex building based on dynamic network flows. Applied Mathematical Modelling 73 (2019) 545–562.

Z. Geng, X. Li, H. Kuang, X. Bai, Y. Fan, 2019. Effect of uncertain information on pedestrian dynamics under adverse sight conditions. Physica A 521 (2019) 681–691.

Z. Zhang, B. Wolshon, V.V. Dixit, 2015. Integration of a cell transmission model and macroscopic fundamental diagram Network aggregation for dynamic traffic models. Transportation Research Part C 55 (2015) 298–309.

Appendix

R Codes for the simulation of the most updated version of evacuation guiding model in the thesis.

```r
rm(list = ls())
#install.packages("igraph")
#install.packages("readxl")
#install.packages("xlsx")
#install.packages("dplyr")

library(igraph)
library(readxl)
library(xlsx)
library(dplyr)
```

Input data of the vessel layout and evacuees

```r
edges <- read_xlsx("network graph.xlsx", sheet = 1)
nodes <- read_xlsx("network graph.xlsx", sheet = 2)
evacuees <- read_xlsx("network graph.xlsx", sheet = 3)
```

Graph network generation

```r
g <- graph.data.frame(edges[,2:3], directed = F)
gz <- graph.data.frame(edges[,2:3], directed = F)
# plot(g)
```

Customized functions

```r
# Define the penalty function on density
pfund <- function(D){
  if (D == 0){
    pd <- 0
  }
  if (D > 0 & D < 0.5){
    Fs = 1.3 * D
    pd <- 1/Fs
  }
  if (D >= 0.5 & D < 1.9){
    Fs = 117/280 + 13/28 * D
    pd <- 1/Fs
  }
  if (D >= 1.9 & D < 3.2){
    Fs = 2.25 - 0.5 * D
    pd <- 1/Fs
  }
  if (D >= 3.2 & D < 3.5){
    Fs = 4.17 - 1.1 * D
    pd <- 1/Fs
  }
```

```
  if (D >= 3.5){
    Fs = 0.32
    pd <- 1/Fs
  }
  return(pd)
}


# Define the speed function for evacuees
spfun <- function(D){
  if (D >= 0 & D < 0.5){
    sp = 1.2
  }
  if (D >= 0.5 & D < 1.9){
    sp = 389/280 - 53/140 * D
  }
  if (D >= 1.9 & D < 3.2){
    sp = 441/325 - 47/130 * D
  }
  if (D >= 3.2 & D < 3.5){
    sp = 19/15 - 1/3 * D
  }
  if (D >= 3.5){
    sp = 0.1
  }
  return(sp)
}

# Define the function of the penalty coefficient on sink capacity
pcfun <- function(AC){
  if (is.na(AC) == TRUE){
    pc = 0
  } else {
    if (AC == 0){
      pc = 99
    }
    if (AC > 0 & AC <= 0.1){
      pc = 10
    }
    if (AC > 0.1 & AC <= 0.2){
      pc = 8
    }
    if (AC > 0.2 & AC <= 0.3){
      pc = 5
    }
    if (AC > 0.3 & AC <= 0.5){
      pc = 3
    }
    if (AC > 0.5 & AC <= 0.6){
      pc = 2
```

```
    }
    if (AC > 0.6 & AC <= 0.8){
      pc = 1
    }
    if (AC > 0.8){
      pc = 0
    }
  }

  return(pc)
}

# Function to calculate equivalent length

# bn - binary (= 1 if the edge is inapplicable to wheelchair users, = 0
 otherwise)
edges$bn <- 0
edges[edges$Stairways == 1 | edges$Width < 1.2, "bn"] <- 1

# Equaivalent length formula
EL <- function(l, pd, D, bo, bs, bz, bn, be, pc, bl){

  L <- l * (1 + pd * D + 99 * bo + 0.15 * bs  + 99 * bz * bn + 99 * (1-
bz) * be
            + pc * bl)
  L <- round(L,0)
  return(L)
}

# Shortest route determination function
edgetosink <- c("39", "62", "58", "53")
sinks <- c("41", "42", "43", "44")
asinks <- c("41", "42", "43", "44")
Dijkstra <- function(g, w){

  dis <- distances(g, v = w, to = asinks,
                   weights = graph_attr(g,"weight"),algorithm = "dijkst
ra")
  targetsink <- colnames(dis)[which.min(dis)]
  spath <- shortest_paths(g, from = w, to = targetsink,
                          weights = graph_attr(g,"weight"),
                          output = "both")
  # which edge to go for next step
  if (length(as.character(spath$epath[[1]])) == 1){
    epath <- as.character(spath$epath[[1]])
  }
  if (length(as.character(spath$epath[[1]])) > 1){
    epath <- strsplit(as.character(spath$epath[[1]]), " ")[[1]]
  }
```

```
  # which node to go for next step
  vpath <- spath$vpath[[1]][2]$name

  return(c(epath,vpath))


}
```

Construct data frames to store data

```
# Data frame for obstacle binary within each edge over time
bodata <- as.data.frame(edges[,2:3])

# Data frame for number of evacuees within each edge over time
ENdata <- as.data.frame(edges[,2:3])
ENdata$Space <- edges$Space

# Data frame for edge densities over time
Ddata <- as.data.frame(edges[,2:3])

# Data frame for edge equivalent length over time
ELdata <- as.data.frame(edges[,2:4])
ELdataz <- as.data.frame(edges[,2:4])

# Data frame for travel time along the edge
TTdatax <- as.data.frame(edges[2:3])
TTdatay <- as.data.frame(edges[2:3])
TTdataz <- as.data.frame(edges[2:3])

# Data frame for shortest routes at each node over time
SRdata <- as.data.frame(nodes[1:40,1])
SRdataz <- as.data.frame(nodes[1:40,1])
NSRdata <- as.data.frame(nodes[1:40,1])
NSRdataz <- as.data.frame(nodes[1:40,1])

# Data frame for each evacuee's movement path over time

EEdata <- as.data.frame(matrix(data = NA, nrow = 100, ncol = 501))

colnames(EEdata) <- unlist(lapply(X=as.character(c(0:500)),
                                  FUN = function(X){paste0("t",X)}))

# Data frame for sink capacity control

# Handle the capacity
SCdata <- as.data.frame(matrix(data = NA, nrow = 4, ncol = 4))
colnames(SCdata) <- c("nsink","esink", "capacity", "acrate")
SCdata$nsink <- c("41", "42", "43", "44")
SCdata$esink <- c("39", "62", "58", "53")
```

```
SCdata$capacity <- rep(25,4)
SCdata$acrate <- (SCdata$capacity)/25
```

Input of the fire emergency

```
bodata$t0 <- rep(0,nrow(bodata))

## Suppose that when t = 0, a fire accident is detected at node 4,
## and emergency evacuation starts.
## At t30, the fire bursts out from node 4,
## and edges (4--6) and (3--4) are marked as out of use after t30.
## After t60, the fire would spread to node 3, therefore edges connecti
ng to
## node 3 are also marked as out of use.
## After t100, the fire would spread to node 5.
## After t120, the fire would spread to node 2.
## After t150, the fire would spread to node 6.
## After t200, the fire would spread to node 7.
## After t240, the fire would spread to node 8 and 14.
## After t280, the fire would spread to node 1 and 12.
## After t300, the fire would spread to node 13 and 24.
## After t350, the fire would spread to node 18 and 19.
## After t420, the fire would spread to node 15 and 16.
## After t450, the fire would spread to node 9, 22 and 25.
## After t480, the fire would spread to node 11, 20 and 34.

# In addition, the elevator is set to break down at t30.

for (t in 1:500){
  bodata[,paste0("t",t)] <- bodata[,paste0("t",t-1)]
  if (t == 30){
    bodata[bodata$u == 4 | bodata$v == 4, paste0("t",t)] <- 1
    bodata[23,paste0("t",t)] <- 1  # elevator break down
  }
  if (t == 60){
    bodata[bodata$u == 3 | bodata$v == 3, paste0("t",t)] <- 1
  }
  if (t == 100){
    bodata[bodata$u == 5 | bodata$v == 5, paste0("t",t)] <- 1
  }
  if (t == 120){
    bodata[bodata$u == 2 | bodata$v == 2, paste0("t",t)] <- 1
  }
  if (t == 150){
    bodata[bodata$u == 6 | bodata$v == 6, paste0("t",t)] <- 1
  }
  if (t == 200){
    bodata[bodata$u == 7 | bodata$v == 7, paste0("t",t)] <- 1
  }
  if (t == 240){
```

```
    bodata[bodata$u == 8 | bodata$v == 8 | bodata$u == 14 | bodata$v ==
 14,
           paste0("t",t)] <- 1
  }
  if (t == 280){
    bodata[bodata$u == 1 | bodata$v == 1 | bodata$u == 12 | bodata$v ==
 12,
           paste0("t",t)] <- 1
  }
  if (t == 300){
    bodata[bodata$u == 13 | bodata$v == 13 | bodata$u == 24 | bodata$v
== 24,
           paste0("t",t)] <- 1
  }
  if (t == 350){
    bodata[bodata$u == 18 | bodata$v == 18 | bodata$u == 19 | bodata$v
== 19,
           paste0("t",t)] <- 1
  }
  if (t == 420){
    bodata[bodata$u == 15 | bodata$v == 15 | bodata$u == 16 | bodata$v
== 16,
           paste0("t",t)] <- 1
  }
  if (t == 450){
    bodata[bodata$u == 9 | bodata$v == 9 | bodata$u == 22 | bodata$v ==
 22 |
             bodata$u == 25 | bodata$v == 25,
           paste0("t",t)] <- 1
  }
  if (t == 480){
    bodata[bodata$u == 11 | bodata$v == 11 | bodata$u == 20 | bodata$v
== 20|
             bodata$u == 34 | bodata$v == 34,
           paste0("t",t)] <- 1
  }
}
```

Look one step ahead of time

```
for (e in 1: nrow(edges)){
  edges$Safe[e] <- sum(bodata[e,]==0)
}
```

Initialization

```
# Initialize number of people within each edge and edge density at t0
ENdata$t0 <- rep(0,nrow(ENdata))
Ddata$t0 <- rep(0,nrow(Ddata))
evacuees$arrived <- 0
# Initialize equivalent length for each length
```

```r
for (e in 1: nrow(edges)){
  ELdata[e, "t0"] <- EL(ELdata[e,"Physical length"], pfund(Ddata[e, "t0"]),
                        Ddata[e, "t0"], bodata[e, "t0"],edges$Stairways[e],
                        0, edges$bn[e], edges$Elevators[e],
                        pcfun(SCdata[match(e, SCdata$esink),"acrate"]),
                        edges$Sink[e])
  if (edges$bn[e] == 0){
    ELdataz[e,"t0"] <- ELdata[e,"t0"]
    }
  if (edges$bn[e] == 1){
      ELdataz[e,"t0"] <- EL(ELdataz[e,"Physical length"], pfund(Ddata[e, "t0"]),
                        Ddata[e, "t0"], bodata[e, "t0"],edges$Stairways[e],
                        1, edges$bn[e], edges$Elevators[e],
                        pcfun(SCdata[match(e, SCdata$esink),"acrate"]),
                        edges$Sink[e])
  }
  # Based on the equivalent length, calculate the travel time along each edge
  # begins at t0.


  if (is.na(match(as.character(e),SCdata$esink)) == TRUE){
    TTdatax[e,"t0"] <- ceiling(ELdata[e,"t0"]/spfun(Ddata[e, "t0"]))
    TTdatay[e,"t0"] <- ceiling(ELdata[e,"t0"]/(0.8*spfun(Ddata[e, "t0"])))
    TTdataz[e,"t0"] <- ceiling(ELdataz[e,"t0"]/(0.6*spfun(Ddata[e, "t0"])))
  } else {
    TTdatax[e,"t0"] <- ceiling(1.15*ELdata[e,3]/spfun(Ddata[e, "t0"]))
    TTdatay[e,"t0"] <- ceiling(1.15*ELdata[e,3]/(0.8*spfun(Ddata[e, "t0"])))
    TTdataz[e,"t0"] <- ceiling(1.15*ELdataz[e,3]/(0.6*spfun(Ddata[e, "t0"])))
  }

}


# For each node, determine the next direction
g <- set_graph_attr(g,"weight",ELdata$t0)
gz <- set_graph_attr(gz, "weight",ELdataz$t0)

for (n in 1:40){
  SRdata[n, "t0"] <- Dijkstra(g,as.character(n))[1]
  SRdataz[n, "t0"] <- Dijkstra(gz,as.character(n))[1]
  NSRdata[n, "t0"] <- Dijkstra(g,as.character(n))[2]
```

```
  NSRdataz[n, "t0"] <- Dijkstra(gz,as.character(n))[2]
}


# For each evacuee, record their movement according to the directions
for (i in 1:nrow(evacuees)){
  if (evacuees$bz[i] == 0){
    edgetogo <- SRdata[match(evacuees$`initial node location`[i], SRdat
a$w), "t0"]
    nodetogo <- NSRdata[match(evacuees$`initial node location`[i], NSRd
ata$w),
                        "t0"]
    if(evacuees$by[i] == 0){
      traveltime <- TTdatax[as.numeric(edgetogo), "t0"]}
    if(evacuees$by[i] == 1){
      traveltime <- TTdatay[as.numeric(edgetogo), "t0"]}
    if(is.na(match(nodetogo,sinks)) == TRUE){
      edgetogo2 <- SRdata[match(nodetogo, SRdata$w), "t0"]
      nodetogo2 <- NSRdata[match(nodetogo, NSRdata$w), "t0"]
      ptime <- 0 + traveltime
      tsafe <- edges$Safe[as.numeric(edgetogo2)]
      if(ptime >= tsafe){
                origin <- ELdata[as.numeric(edgetogo),"t0"]
                ELdata[as.numeric(edgetogo),"t0"] <- 999
                g <- set_graph_attr(g,"weight",ELdata$t0)
                ELdata[as.numeric(edgetogo),"t0"] <- origin
                edgetogo <- Dijkstra(g,evacuees$`initial node location`
[i])[1]
                nodetogo <- Dijkstra(g,evacuees$`initial node location`
[i])[2]
                g <- set_graph_attr(g,"weight",ELdata$t0)

                if (evacuees$by[i] == 0){
                      traveltime <- TTdatax[as.numeric(edgetogo), "t0"]
                }
                if (evacuees$by[i] == 1){
                      traveltime <- TTdatay[as.numeric(edgetogo), "t0"]
                }
              }
    }
  }


  if(evacuees$bz[i] == 1){
    edgetogo <- SRdataz[match(evacuees$`initial node location`[i], SRda
taz$w),
                        "t0"]
    nodetogo <- NSRdataz[match(evacuees$`initial node location`[i], NSR
dataz$w),
                         "t0"]
```

```
    traveltime <- TTdataz[as.numeric(edgetogo), "t0"]
    if (is.na(match(nodetogo,sinks)) == TRUE){
      edgetogo2 <- SRdataz[match(nodetogo, SRdataz$w), "t0"]
      nodetogo2 <- NSRdataz[match(nodetogo, NSRdataz$w), "t0"]
      ptime <- 0 + traveltime
      tsafe <- edges$Safe[as.numeric(edgetogo2)]
      if(ptime >= tsafe){
              origin <- ELdataz[as.numeric(edgetogo),"t0"]
              ELdataz[as.numeric(edgetogo),"t0"] <- 999
              gz <- set_graph_attr(gz,"weight",ELdataz$t0)
              ELdataz[as.numeric(edgetogo),"t0"] <- origin
              edgetogo <- Dijkstra(gz,evacuees$`initial node location`
[i])[1]
              nodetogo <- Dijkstra(gz,evacuees$`initial node location`
[i])[2]
              gz <- set_graph_attr(gz,"weight",ELdataz$t0)
              traveltime <- TTdataz[as.numeric(edgetogo), "t0"]

            }

        }
      }

  EEdata[i,1:traveltime] <- edgetogo

  evacuees$currentnode[i] <- nodetogo
  evacuees$numofnode[i] <- 1
  evacuees$TTT[i] <- traveltime
  evacuees$node1[i] <- nodetogo
  evacuees$tt1[i] <- traveltime

  if (is.na(match(evacuees$currentnode[i],sinks)) == FALSE){
    evacuees$arrived[i] <- 1
    SCdata[match(evacuees$currentnode[i], sinks), "capacity"] <-
      SCdata[match(evacuees$currentnode[i], sinks), "capacity"]-1
    SCdata[match(evacuees$currentnode[i], sinks), "acrate"] <-
      SCdata[match(evacuees$currentnode[i], sinks), "capacity"]/25
  }

}
```

Loop to fill in all kinds of data over time

```
for (t in 1:500){
  for (e in 1:nrow(edges)){
    ENdata[e,paste0("t",t)] <- sum(na.omit(EEdata[1:95,paste0("t",t)])
                                   == as.character(e)) +
      2 * sum(na.omit(EEdata[96:100,paste0("t",t)]) == as.character(e))
    Ddata[e,paste0("t",t)] <- round(ENdata[e,paste0("t",t)]/ENdata[e, "
Space"],2)
```

```
    ELdata[e,paste0("t",t)] <- EL(ELdata[e,"Physical length"],
                                  pfund(Ddata[e, paste0("t",t)]),
                                  Ddata[e, paste0("t",t)],
                                  bodata[e, paste0("t",t)],
                                  edges$Stairways[e],
                                  0,
                                  edges$bn[e],
                                  edges$Elevators[e],
                                  pcfun(SCdata[match(e, SCdata$esink),"
acrate"]),
                                  edges$Sink[e])

    if (edges$bn[e] == 0){
      ELdataz[e,paste0("t",t)] <- ELdata[e,paste0("t",t)]
    }
      else {
        ELdataz[e,paste0("t",t)] <- EL(ELdata[e,"Physical length"],
                                    pfund(Ddata[e, paste0("t",t)]),
                                    Ddata[e, paste0("t",t)],
                                    bodata[e, paste0("t",t)],
                                    edges$Stairways[e],
                                    1,
                                    edges$bn[e],
                                    edges$Elevators[e],
                                    pcfun(SCdata[match(e, SCdata$esin
k),"acrate"]),
                                    edges$Sink[e])
      }
    if (is.na(match(as.character(e),SCdata$esink)) == TRUE){
      TTdatax[e,paste0("t",t)] <- ceiling(ELdata[e,paste0("t",t)]/
        spfun(Ddata[e, paste0("t",t)]))
      TTdatay[e,paste0("t",t)] <- ceiling(ELdata[e,paste0("t",t)]/
        (0.8 * spfun(Ddata[e, paste0("t",t)])))
      TTdataz[e,paste0("t",t)] <- ceiling(ELdataz[e,paste0("t",t)]/
        (0.6 * spfun(Ddata[e, paste0("t",t)])))
    } else {
      TTdatax[e,paste0("t",t)] <- ceiling(ELdata[e,3]/
        spfun(Ddata[e, paste0("t",t)]))
      TTdatay[e,paste0("t",t)] <- ceiling(ELdata[e,3]/
        (0.8 * spfun(Ddata[e, paste0("t",t)])))
      TTdataz[e,paste0("t",t)] <- ceiling(ELdataz[e,3]/
        (0.6 * spfun(Ddata[e, paste0("t",t)])))
    }

    }


    g <- set_graph_attr(g,"weight",ELdata[,paste0("t",t)])
    gz <- set_graph_attr(gz, "weight",ELdataz[,paste0("t",t)])
```

```
  for (n in 1:40){
    SRdata[n, paste0("t",t)] <- Dijkstra(g,as.character(n))[1]
    SRdataz[n, paste0("t",t)] <- Dijkstra(gz,as.character(n))[1]
    NSRdata[n, paste0("t",t)] <- Dijkstra(g,as.character(n))[2]
    NSRdataz[n, paste0("t",t)] <- Dijkstra(gz,as.character(n))[2]

  }


  for (i in 1:100) {
    if (is.na(EEdata[i,paste0("t",t)]) == TRUE) {
      if (is.na(match(evacuees$currentnode[i],sinks)) == TRUE) {
        if (evacuees$bz[i] == 0) {
          edgetogo <- SRdata[match(evacuees$currentnode[i],SRdata$w),
                             paste0("t",t)]
          nodetogo <- NSRdata[match(evacuees$currentnode[i], NSRdata
$w),
                              paste0("t",t)]
          if (evacuees$by[i] == 0) {
            traveltime <- TTdatax[as.numeric(edgetogo), paste0("t",t)]
          }
          if (evacuees$by[i] == 1) {
            traveltime <- TTdatay[as.numeric(edgetogo), paste0("t",t)]
          }
          if (is.na(match(nodetogo,sinks)) == TRUE){
            edgetogo2 <- SRdata[match(nodetogo, SRdata$w), paste0("t",
t)]

            nodetogo2 <- NSRdata[match(nodetogo, NSRdata$w), paste0("t
",t)]
            ptime <- t + traveltime
            tsafe <- edges$Safe[as.numeric(edgetogo2)]
              if(ptime >= tsafe){
                origin <- ELdata[as.numeric(edgetogo),paste0("t",t)]
                ELdata[as.numeric(edgetogo),paste0("t",t)] <- 999
                g <- set_graph_attr(g,"weight",ELdata[,paste0("t",t)])
                ELdata[as.numeric(edgetogo),paste0("t",t)] <- origin
                edgetogo <- Dijkstra(g,evacuees$currentnode[i])[1]
                nodetogo <- Dijkstra(g,evacuees$currentnode[i])[2]
                g <- set_graph_attr(g,"weight",ELdata[,paste0("t",t)])

                if (evacuees$by[i] == 0){
                      traveltime <- TTdatax[as.numeric(edgetogo), paste
0("t",t)]
                }
                if (evacuees$by[i] == 1){
                      traveltime <- TTdatay[as.numeric(edgetogo), paste
0("t",t)]
                }
```

```
       }
     }
    } else {
      edgetogo <- SRdataz[match(evacuees$currentnode[i],
                 SRdataz$w),paste0("t",t)]
      nodetogo <- NSRdataz[match(evacuees$currentnode[i],
                  NSRdataz$w), paste0("t",t)]
      traveltime <- TTdataz[as.numeric(edgetogo), paste0("t",t)]
      if (is.na(match(nodetogo,sinks)) == TRUE){
       edgetogo2 <- SRdataz[match(nodetogo, SRdataz$w), paste0("
t",t)]

       nodetogo2 <- NSRdataz[match(nodetogo, NSRdataz$w), paste0
("t",t)]

       ptime <- t + traveltime
       tsafe <- edges$Safe[as.numeric(edgetogo2)]
       if(ptime >= tsafe){
        origin <- ELdataz[as.numeric(edgetogo),paste0("t",t)]
        ELdataz[as.numeric(edgetogo),paste0("t",t)] <- 999
        gz <- set_graph_attr(gz,"weight",ELdata[,paste0("t",
t)])

        ELdataz[as.numeric(edgetogo),paste0("t",t)] <- origin
        edgetogo <- Dijkstra(gz,evacuees$currentnode[i])[1]
        nodetogo <- Dijkstra(gz,evacuees$currentnode[i])[2]
        gz <- set_graph_attr(gz,"weight",ELdata[,paste0("t",
t)])

        traveltime <- TTdataz[as.numeric(edgetogo), paste0("t",
t)]


      }
     }
    }

  EEdata[i,(t+1):(t+traveltime)] <- edgetogo
  evacuees$currentnode[i] <- nodetogo
  evacuees$numofnode[i] <- evacuees$numofnode[i] + 1
  evacuees$TTT[i] <- evacuees$TTT[i] + traveltime
  evacuees[i, paste0("node", evacuees$numofnode[i])] <- nodetogo
  evacuees[i, paste0("tt", evacuees$numofnode[i])] <- traveltime

  if (is.na(match(evacuees$currentnode[i],sinks)) == FALSE){
   evacuees$arrived[i] <- 1
   SCdata[match(evacuees$currentnode[i], sinks), "capacity"] <-
    SCdata[match(evacuees$currentnode[i], sinks), "capacity"]-1
   SCdata[match(evacuees$currentnode[i], sinks), "acrate"] <-
    SCdata[match(evacuees$currentnode[i], sinks), "capacity"]/25
   for (s in 1: length(asinks)){
    if (SCdata$capacity[match(asinks[s],SCdata$nsink)] == 0){
     asinks <- asinks[-match(asinks[1],SCdata$nsink)]

    for (n in 1:40){
```

```
          SRdata[n, paste0("t",t)] <- Dijkstra(g,as.character(n))[1]
          SRdataz[n, paste0("t",t)] <- Dijkstra(gz,as.character(n))[1]
          NSRdata[n, paste0("t",t)] <- Dijkstra(g,as.character(n))[2]
          NSRdataz[n, paste0("t",t)] <- Dijkstra(gz,as.character(n))[2]

        }
        break
      }
    }

    }
    }
  }

  }

}
```

Save the result

```
#write.xlsx(evacuees, "Output-vpath4.xlsx", sheetName = "vpath")
#write.xlsx(EEdata, "Output-epath4.xlsx", sheetName = "epath")
#write.xlsx(SCdata, "Output-capacity4.xlsx", sheetName = "capacity")
```

Network Graph Sheet 1

nm	u	v	Physical length	Width	Stairways	Elevators	Space	Sink
1	1	2	40	1.5	0	0	60	0
2	1	11	40	1.5	0	0	60	0
3	1	22	20	2	1	0	40	0
4	2	3	15	1.5	0	0	22.5	0
5	2	12	40	1	0	0	40	0
6	3	4	15	1	0	0	15	0
7	3	5	10	1.5	0	0	15	0
8	3	24	20	1.5	1	0	30	0
9	4	6	30	1	0	0	30	0
10	5	7	20	1.5	0	0	30	0
11	5	14	40	1.5	0	0	60	0
12	6	7	15	1	0	0	15	0
13	7	8	20	1.5	0	0	30	0
14	8	9	25	1.5	0	0	37.5	0
15	8	16	40	1	0	0	40	0
16	9	10	40	1	0	0	40	0
17	9	17	40	1.5	0	0	60	0
18	9	29	20	2	1	0	40	0
19	11	12	40	1.5	0	0	60	0
20	11	32	20	2	1	0	40	0
21	12	13	15	1.5	0	0	22.5	0
22	12	18	15	1	0	0	15	0
23	13	14	10	1.5	0	0	15	0
24	13	19	15	1	0	0	15	0
25	13	34	15	1.5	0	1	4	0
26	14	15	30	1.5	0	0	45	0
27	15	16	10	1.5	0	0	15	0
28	15	20	15	1	0	0	15	0
29	16	17	25	1.5	0	0	37.5	0
30	17	21	20	1	0	0	20	0
31	17	37	20	2	1	0	40	0
32	18	19	15	1	0	0	15	0
33	19	20	30	1	0	0	30	0
34	20	39	20	1.5	1	0	30	0
35	22	23	40	1.5	0	0	60	0
36	22	32	40	1.5	0	0	60	0
37	23	24	15	1.5	0	0	22.5	0
38	23	33	40	1.5	0	0	60	0
39	23	41	15	1.5	0	0	22.5	1
40	24	25	12	1.5	0	0	18	0
41	24	34	40	1.5	0	0	60	0
42	25	26	15	1.5	0	0	22.5	0
43	25	35	40	1	0	0	40	0
44	26	27	25	1	0	0	25	0
45	26	28	45	1.5	0	0	67.5	0
46	26	30	10	1.5	0	0	15	0
47	27	29	25	1	0	0	25	0
48	28	29	10	1.5	0	0	15	0
49	29	37	40	1.5	0	0	60	0
50	30	31	45	1.5	0	0	67.5	0
51	30	36	30	1.5	0	0	45	0
52	31	37	40	1.5	0	0	60	0
53	31	44	15	1.5	0	0	22.5	1
54	32	33	40	1.5	0	0	60	0
55	33	34	15	1.5	0	0	22.5	0
56	34	35	12	1.5	0	0	18	0
57	35	36	15	1.5	0	0	22.5	0
58	35	43	15	1.5	0	0	22.5	1
59	36	39	10	1.5	0	0	15	0
60	37	40	10	1.5	0	0	15	0
61	38	39	42	1.5	0	0	63	0
62	38	42	15	1.5	0	0	22.5	1
63	39	40	50	1.5	0	0	75	0

Network Graph Sheet 2

Network Graph Sheet 3

w	initialX	initialY	initialZ
1	1	0	0
2	0	8	0
3	3	0	0
4	0	0	0
5	0	0	1
6	1	2	0
7	0	4	0
8	2	4	0
9	0	0	0
10	2	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	2
15	1	0	1
16	0	3	0
17	0	0	0
18	0	2	0
19	1	0	0
20	0	0	0
21	0	3	0
22	2	0	0
23	0	0	0
24	1	1	0
25	2	6	1
26	4	5	0
27	4	0	0
28	0	2	0
29	0	3	0
30	0	2	0
31	0	0	0
32	2	0	0
33	2	2	0
34	0	0	0
35	0	0	0
36	0	4	0
37	0	2	0
38	0	0	0
39	2	3	0
40	5	4	0
41	0	0	0
42	0	0	0
43	0	0	0
44	0	0	0

Evacuee	initial node	by	bz
1	1	0	0
2	3	0	0
3	3	0	0
4	3	0	0
5	6	0	0
6	8	0	0
7	8	0	0
8	10	0	0
9	10	0	0
10	15	0	0
11	19	0	0
12	22	0	0
13	22	0	0
14	24	0	0
15	25	0	0
16	25	0	0
17	26	0	0
18	26	0	0
19	26	0	0
20	26	0	0
21	27	0	0
22	27	0	0
23	27	0	0
24	27	0	0
25	32	0	0
26	32	0	0
27	33	0	0
28	33	0	0
29	39	0	0
30	39	0	0
31	40	0	0
32	40	0	0
33	40	0	0
34	40	0	0
35	40	0	0
36	2	1	0
37	2	1	0
38	2	1	0
39	2	1	0
40	2	1	0
41	2	1	0
42	2	1	0
43	2	1	0
44	6	1	0
45	6	1	0
46	7	1	0
47	7	1	0
48	7	1	0
49	7	1	0
50	8	1	0
51	8	1	0
52	8	1	0
53	8	1	0
54	16	1	0
55	16	1	0
56	16	1	0
57	18	1	0
58	18	1	0
59	21	1	0
60	21	1	0
61	21	1	0
62	24	1	0
63	25	1	0
64	25	1	0
65	25	1	0
66	25	1	0
67	25	1	0
68	25	1	0
69	26	1	0
70	26	1	0
71	26	1	0
72	26	1	0
73	26	1	0
74	28	1	0
75	28	1	0
76	29	1	0
77	29	1	0
78	29	1	0
79	30	1	0
80	30	1	0
81	33	1	0
82	33	1	0
83	36	1	0
84	36	1	0
85	36	1	0
86	36	1	0
87	37	1	0
88	37	1	0
89	39	1	0
90	39	1	0
91	39	1	0
92	40	1	0
93	40	1	0
94	40	1	0
95	40	1	0
96	5	0	1
97	14	0	1
98	14	0	1
99	15	0	1
100	25	0	1