Analysis of evacuation performance of early stage ship designs using a Markov Decision Process model

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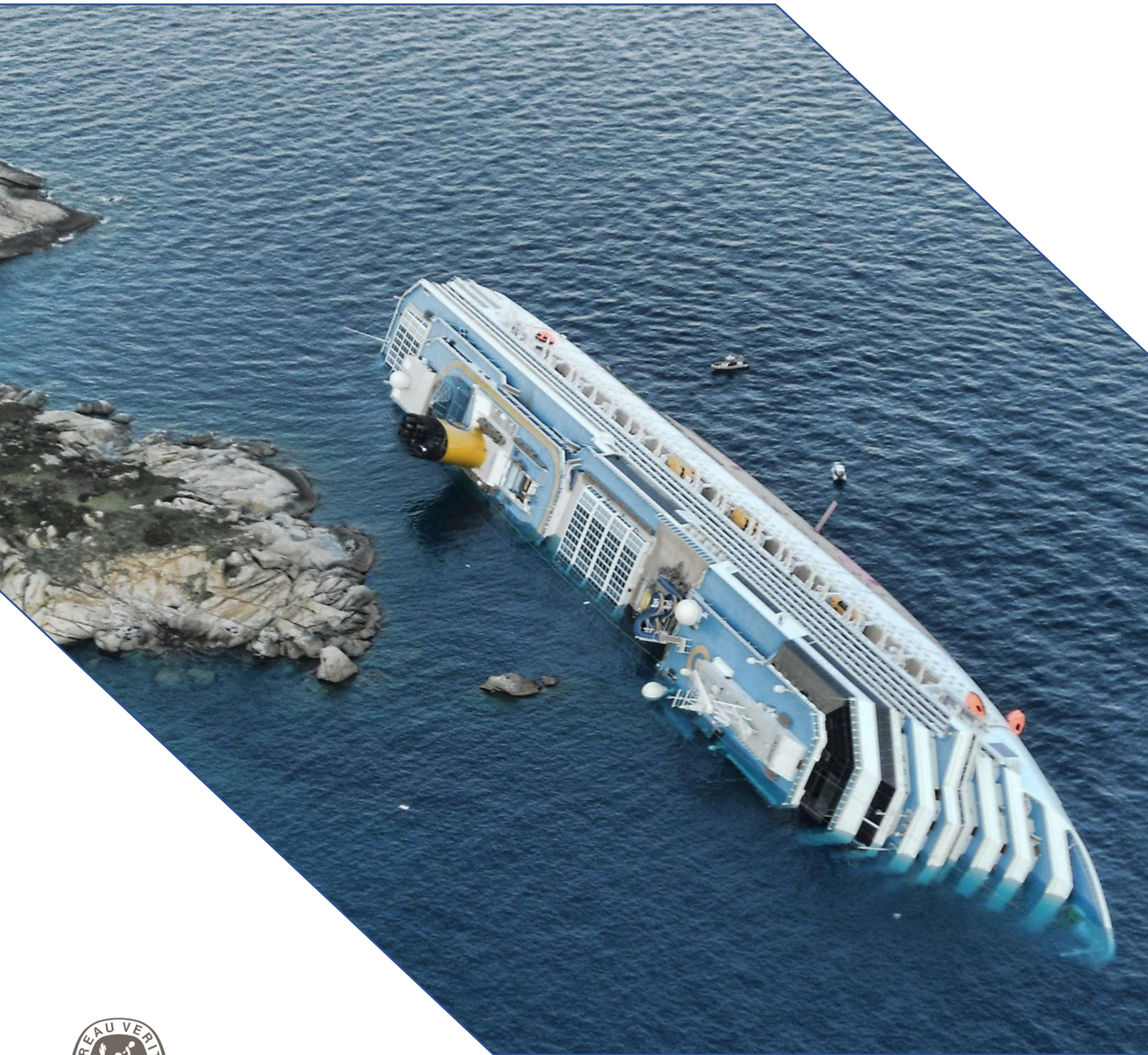

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Analysis of evacuation performance of early stage ship designs using a Markov-Decision-Process model

by

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Summary

This thesis research is conducted on behalf of the Delft University of Technology and Bureau Veritas Rotterdam BV, and the goal is to improve ship evacuation by analyzing this aspect early on in the design process. First, this summary will provide a background on the difficulties involved with the ship evacuation process . Next, an explanation is given why this thesis proposes a different model. And lastly, how this model is validated is elaborated upon.

A ship evacuation is a highly complex process and it is one of the most important aspects concerning the safety of crew and passengers on-board. This process is affected by various factors, largely by the general arrangement. The layout of a ship varies throughout the design period but the most design freedom occurs during the early stage [1]. An estimated 90% of the decisions which have major impact on final design have been made in this stage [2]. As a result, this stage holds the most potential to improve the ship evacuation performance. This stage is characterized by a lack of detailed layout information available, which results in reduced accuracy in evacuation prediction. As of 1st of July 2020 all passenger ships with more than 36 passengers have to perform an evacuation analysis based on guidelines created by the International Maritime Organization (IMO) [3]. The guidelines describe two methods, a simplified method for the early design stage, and an advanced method for the detailed or final design stage. The simplified method translates the ship design to a hydraulic network which in turn results in various method limitations. The goal of an evacuation analysis is, among other things, to provide the designer with information about possible congestion points, identify areas of counter- and cross flows, prove that the escape arrangements are sufficiently flexible, and prove that the evacuation time does not exceed a threshold.

Evacuation models capable of performing an evacuation analysis tend to have four general components that define the various aspects influencing the process. The four components are configuration, environmental, procedural, and behavior component [4]. Including evacuee behavior in an evacuation model tends to be difficult due to the complexity [5] and lack of research available [6]. Evacuation models can be categorized using various descriptors [7–11] however resolution tends to dominate. High resolution models are called macroscopic models whereas low resolution models are called microscopic models. Microscopic models simulate each individual evacuee as an agent with certain attributes, such as walking speed and destination. Most early stage evacuation analysis are macroscopic models and simulate the population as a whole. A different macroscopic approach is proposed by Kana and Singer [12], which uses probability theory to incorporate the stochastic nature of an evacuation process. This method consists of a Markov-Decision-Process (MDP) to calculate the most probable evacuation routes. Policies are determined for each small geometric area, called a state, in the layout. These policies affect evacuation routes. The evacuation process can then be simulated by using the MDP policies and an initial population distribution. The initial population distributions are defined by the Fire Safety Systems Code [13]. Design variations can be compared based on the calculated optimal routes, the time it takes for the process to converge, and how the population is distributed among the exits. A lack of literature is noticed that investigates the relationship between early stage ship design and the ship evacuation performance. Two different studies were found which can be used to validate the MDP methodology.

The first validation study determines which exit configuration is most optimal from an egress perspective. Kurdi *et al.* [14] defined four different layouts for two population sizes. Having exits on all sides was determined to be the most efficient layout. The MDP model consisted of the same setup as the validation study [14]. The MDP method is able to identify the same exit configuration as most efficient based on the population distributed among the exits and simulation convergence times. The second validation study evaluates two different frigate layouts with varying passageway configuration [13, 15]. One layout has a single passageway throughout the ship. The other layout has a parallel passageway configuration. Casarosa [15] used a microscopic model to calculate a range of performance metrics for 7 different scenarios.

All evacuees were modeled as singular agents with different behavior and objectives. 3 out of 7 scenarios were emergency scenarios, where only 1 scenario corresponds with the MDP assumptions. Discrepancy between models is considered as a result of limited, and confidential, layout information used by Casarosa [15]. The MDP method was able to differentiate between the two layout configurations and can identify critical areas in the layout. However, due to the assumptions, it cannot be determined to what extend the method inputs were similar. Nevertheless, both validation studies showed the potential of using a Markov-Decision-Process based method to evaluate early stage ship designs on evacuation performance.

Preface

The drive to continue studying after finishing my bachelor at the NHL University of Applied sciences, led to my enrollment at the Delft University of Technology. The motivation behind this next step was to further improve myself and take on more complex problems. This thesis is my final achievement at the TU Delft and I am eager to embark on new challenges. I could not have achieved this without the help and support of many.

First, I want to thank Austin Kana who supervised my progress. Austin first pitched the idea behind this thesis in his dissertation. I am grateful for his trust in continuing his idea and take it a step further. In addition, his enthusiasm for the topic and involvement throughout the months was much appreciated. Also, I thank Hans Hopman for sharing his experience in ship design and being critical on my work. His comments and suggestions guided me towards my goal.

Next, I wish to thank Nick Daniels who, with his extensive experience and knowledge of regulations, was always available to give feedback and new insights. The regulatory framework is not easy to comprehend in such a short period, even after having worked at Bureau Veritas myself for almost three years. His guidance greatly reduced my struggle to get a clear picture of all relevant rules. Likewise, I would thank all colleagues at Bureau Veritas, with special thanks to Krasimira Charchieva and Frank Kersbergen. Both spend time making sure I found what I was looking for, and that I understood it correctly. This was greatly appreciated.

Last but not least, I would like to thank my family for always supporting my decision to continue studying, even if it took a bit longer than expected. Help was always there when I needed it, and confidence in my ability to finish this thesis. In addition, I want to express gratitude towards my friends who always stood ready for support, showed interest in my work, and made sure I was still getting enough fun.

R.S. Joustra
Delft, September 2018

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Introduction

1.1. Background

In 2016 there were 2,611 maritime shipping incidents. In EU states or vessels sailing under one of the EU state flags, 976 persons were injured and 115 fatalities occurred due to shipping incidents [19]. During the last 10 years the number of casualties in maritime shipping incidents declined, there is no room for complacency [20]. Casualties and/or loss of life can occur when passengers cannot get on time to the life vessels or when passengers are unable to leave the vessel in time the first place. Much research is spent on improving maritime shipping safety, starting from the titanic incident resulting in the creation of Safety Of Life At Sea (SOLAS) in 1914. The mission of the International Maritime Organization (IMO) is to promote safe, secure, environmentally sound, efficient and sustainable shipping through cooperation. One of the challenges involved is the evacuation of crew and passengers on vessels during an emergency. Such an emergency follows after certain events occurring on a vessel. The events leading up to an evacuation could be, for example, due to a fire or flooding [21].

The evacuation progress depends on a multitude of factors including, but not limited to, the number of passengers, population demographics, type of hazard, training of crew, protocols or the layout of the vessel. Ship arrangement design heavily influences evacuation of passenger and crew during an emergency. From all possible locations in a ship, the evacuation routes should be known. However, passengers often are not familiar with the layout of the ship resulting in difficulty to egress. Width of stairways and hallways influence the flow rate possible through the ship. There should be enough information available to guide passengers towards safety by means of, for example, evacuation signs or emergency lighting [22].

Evacuation is one of the most important aspects concerning the safety of those on board [23]. An evacuation analysis gives insight in how individuals move throughout the vessel during an emergency and can be used to, for example, evaluate potential congestion points. In may 2016 the IMO approved revised guidelines making evacuation analysis mandatory both for ro-ro passenger vessels as well as other passenger ships constructed on or after the first of January 2020. MSC.1/Circ.1533 also recommends that the guidelines are used in early design process. This to enable designers to identify congestion points or critical areas [24]. The regulation changes also give rise to a demand in more insight in egress modeling.

Improving evacuation time is beneficial from a safety perspective but can also be beneficial from a financial perspective. The vessel layout is defined in early stages of ship design and is mostly fixed after that. Changes in design layout in late-stage is difficult to implement. Hence, to assess the ship layout from an egress perspective in early stage ship design could prove beneficial in evacuation performance when the ship is operational.

An evacuation analysis can either be a simplified analysis based on formulas provided by IMO or an advanced analysis where the movement of each person is considered [25]. The latter could be a multi-agent simulation or velocity based personal movement models. Examples of software for building emergency evacuation simulations are, for example, flow based, cellular automata, agent-based, and activity based [26]. Examples of software capable of simulation egress are EVACNET4, WAYOUT, PathFinder, and EGRESS 2002.

Due to the size and complexity of new vessels, modeling evacuation patterns in early stage becomes harder. Multi-agent simulations and/or velocity based personnel movements models are both computational expensive aswell as require a detailed layout of the vessel. The focus for this thesis will be on the combination of early stage ship design and egress possibilities within this domain. Kana and Singer [12], Kana and Droste [27] proposed an Markov-Decision-Process (MDP) to model evacuation and the studies showed potential for the MDP ability to simulate evacuation. This thesis will expand upon said research.

1.2. Research objective

The main objective of this thesis will be to research if and how Ship-Centric Markov Decision Process (SC-MDP) could be used for an early stage design model used for egress modeling. The main question:

How does a ship design alter when it is egress based driven and could a Ship-Centric Markov Decision Process provide a tool for such a method in the early design stage?

To answer the above question several sub questions should be also answered.

1. *For which types of vessels does egress influence the design and how do other industries simulate egress?*
2. *What information is necessary for an egress model as input and what information should the model provide the designer.*
3. *How does general arrangement design influence egress?*
4. *Is an SC-MDP a viable method for modeling egress in general and which aspects of egress is it able to capture?*

1.3. Method proposal

The SC-MDP is utilizes a Markov Decision Processes, which is an extension of Markov chains. A Markov chain describes how a process changes through time in case future and past events are independent. Meaning that any decision made in its current state does not depend on past decisions. A Markov chain consists of states in which a system can be in. The transition matrix gives the probability to leap from state to state. The probability to be located in a state at a certain epoch is given by the state vector s.

An example of a transition probability graph is given in the Figure 1.1. This graphically show two states the system can be in and the respective probabilities to change from one state to another or to stay (p_{ij}) in the same state. A Markov decision process gives a sequence of Markov chains for each decision made, in this case for each state change. As described in *Artificial Intelligence: a modern approach*[28], a Markov decision process is a sequential decision problem for a fully observable (the agent always knows where it is), stochastic environment with a Markovian transition model (decision for the next state does not depend on previous states) and additive rewards.

A Markov-Decision-Process consists of decisions and expected utilities. For egress modeling, rewards will influence how a person will move through the ship, avoiding a fire for example. The rewards function as an incentive for agents to evacuate. Next, a state represent a small area, the actions represent the movement of an individual or, the population, in this case the rewards could simulate the pain individuals or a population suffers during the evacuation, and the transition matrix represents the probability of moving from state to state choosing certain actions.

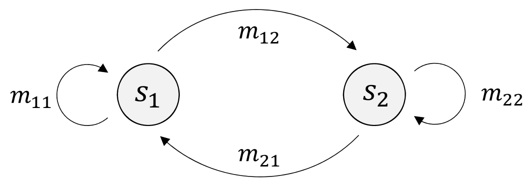


Figure 1.1: Graphical representation of a Markov-Chain with two states

The method will be validated using two validation studies. The first study determines the ability for an MDP to differentiate between different designs where the exits are placed at different locations. A recently published article by Kurdi *et al.* [14] investigated this problem. By comparing outcomes and conclusions the MDP model can be validated. The second study is done by Casaroza [15], which, among other things, investigated the influence of passageway configuration on evacuation performance. Similarly, a different design aspect is varied to study the influence on personnel movement. The second validation study will determine if the MDP is also able to identify critical areas and give the ship designer information needed to further optimize and improve the safety of the design.

2
Literature study

2.1. Regulation

An evacuation analysis is a method which gives the designer insight regarding the evacuation performance of a design. For certain ships such an analysis can be mandatory depending under which flag it sails. The international Maritime Organization (IMO) created the Safety Of Life At Sea (SOLAS) convention which stipulates regulations including the assessment of the evacuation performance. If a country has signed this treaty all ships sailing under their flag has to fulfill SOLAS requirements. IMO amends the convention on a regular basis and as such the industry has to adapt to new regulations. The regulations are a starting point to get a better understanding for which ships an evacuation analysis is mandatory, why this is mandatory and what the main objective or goals are for these analysis. Many of the evacuation simulation tools are developed with the changes in requirements and the introduction of Circ. 909 being a stimuli [9, 29–32]. Therefore this section will describe the regulation regarding evacuation criteria.

SOLAS and Fire Safety Systems (FSS) are conventions regulating means of escape for the ships of interest. These conventions are all setup through IMO. Classification societies may have added regulations of their own to provide additional service for the industry. The IMO will be used as the main source regarding a mandatory evacuation analysis. Different regulatory bodies have their own regulations which quickly makes the domain arduous to map. Therefore classification societies, flag states, port authorities and the such are left out of the scope.

The IMO regulations has been used as a basis to determine for which ships an evacuation analysis is mandatory. The SOLAS convention was adopted in 1914 in response of the titanic disaster. Four versions followed after the 1914 version, these came into force in 1929, 1948, 1960 and 1974 [33]. From then on, multiple amendments have been made. A distinction is made between amendments and circulars. If a flag state ratifies SOLAS, then all amendments are also ratified and should be incorporated into law of the flag state. Circulars however, provide guidelines and additional information and are not mandatory. Flag states can choose to ratify certain circulars and make them mandatory for all ships sailing under this flag.

2.1.1. Safety Of Life At Sea, SOLAS

Regulations tend to be reformed after major disasters. After the Herald of the Free Enterprise disaster (1984) and the Estonia disaster (1994) IMO made evacuation analysis mandatory for ro-ro passenger ships [34]. Both disasters resulted in a great loss of life. This evacuation analysis regulation was implemented after the 1995 conference of Safety Of Life At Sea '95, expanding regulation 28 to include:

.3 Requirements applicable to ro-ro passenger ships constructed on or after 1 July 1999
For ro-ro passenger ships constructed on or after 1 July 1999, escape routes shall be evaluated by an evacuation analysis early in the design process. The analysis shall be used to identify and eliminate, as far as practicable, congestion which may develop during an abandonment,...

After consolidated 2014 version, as of now, there have been 8 amendments which have a date of entry ranging from 1/7/2014 to 1/1/2020. These are amendments 365(93), 366(93), 380(94), 386(94), 392(95), 395(95), 404(96) and 409(97). The amendments containing regulation changes regarding evacuation is 404(96). Therefore, SOLAS consolidated edition 2014 and MSC.404(96) are used to categorize the requirements from an evacuation analysis perspective. Anything not resulting in a mandatory evacuation analysis is left out of the scope. Only ro-ro passenger ships are required to perform this analysis for the consolidated 2014 SOLAS version, whereas for regular passenger ships a reference is to a circular. This circular is MSC.1/Circ.1533 which contains guidelines on how to perform an evacuation analysis conform IMO standards. MSC.404(96) stipulates that other passenger ships constructed on or after 1 January 2020 should also perform an evacuation analysis. Researching which countries ratified the circular has not been done, since as of 2020 all passengers ships carrying more than 36 passengers have to perform an evacuation analysis.

Regulation 13 - Means of escape

Regulation 13 contains the mandatory evacuation analysis. A reference is made to MSC.1/Circ.1533 at the title of paragraph §3.2.7. Amendment MSC.404(96) changed regulation 13, where the mandatory evacuation analysis was previously defined under paragraph §7.4, it is now be defined as given below. The in bold accentuated sentence parts give an indication of some of the desired objectives of the analysis.

3.2.7.1 ***Escape routes shall be evaluated by an evacuation analysis early in the design process.*** *This analysis shall apply to:*
.1 ro-ro passenger ships constructed on or after 1 July 1999; and
.2 other passenger ships constructed on or after 1 January 2020 carrying more than 36 passengers.

3.2.7.2 The analysis shall be used to ***identify and eliminate****, as far as practicable,* ***congestion*** *which may develop during an abandonment, due to normal movement of passengers and crew along escape routes, including the* ***possibility that crew may need to move along these routes in a direction opposite to the movement of passengers****. In addition, the analysis shall be used to demonstrate that* ***escape arrangements are sufficiently flexible*** *to provide for the possibility that certain escape routes, assembly stations, embarkation stations or survival craft may not be available as a result of a casualty.*

Safe return to port

SOLAS II-2/21 Safe return to port states that certain ships should be able to return to port after a hazardous event. Passenger ships constructed on or after 1 July 2010 having a length of 120 m or more, or having three or more main vertical zones should be able to return to port under its own propulsion after a casualty threshold is exceeded. This casualty threshold is defined in a context of a fire, and further described in SOLAS II-2 21.3. Next to this a list of 14 items are given stipulating systems that shall remain operational and hence not be affected by a fire. Apart from these systems, a safe area should also be incorporated in the design which ensures that the health of crew and passengers are remained. Such an area should contain sanitation, water, food, and more basic services [3].

MSC.1/Circ.1533

MSC1./Circ.1533 contains the revised guidelines on evacuation analysis for new and existing passenger ships. In may 2016 the Maritime Safety Committee approved the guidelines as a guide for making evacuation analysis. The SOLAS regulation are changed to make evacuation analysis mandatory both for ro-ro passenger and other passenger ships constructed after 1 January 2020. The guidelines provided two different methods. The first described method is a simplified analysis and the second method as a more advanced analysis. The aim of the analysis is to compare the performance of the ship with benchmark scenarios instead of simulating actual evacuation. At this moment there is still a lack of actual verification data and therefore the guidelines are mostly based on data coming from the civil building industry [24]. The guidelines suggest for the evacuation analysis on existing passenger ships to focus on identifying critical areas.

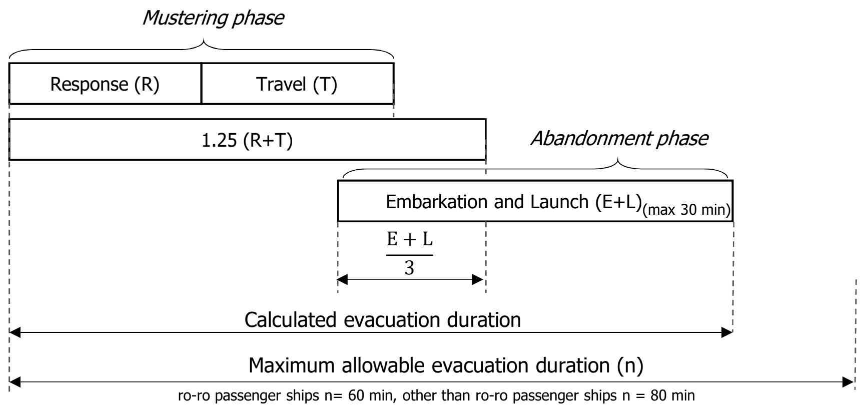


Figure 2.1: Performance standard according to IMO [16].

The performance standard of IMO regarding allowable evacuation duration's are given in Figure 2.1. The mustering phase consist of a response duration (R) and a travel duration (T). After this embarkation and launch follows for which the duration is denoted as (E+L). The evacuation duration's specified by IMO is based on an analysis of fire risk [16]. These durations combined will give an indication of the evacuation duration. However, there can still be a difference between estimated evacuation times and actual estimation times due to, for example, inadequate evacuation planning [35].

A minimum of four scenarios should be considered, combining primary and secondary cases with day and night scenarios. The primary cases are in accordance with chapter 13 of the FSS code and the calculation shall be done for each main vertical zone. The secondary case will focus on the zones generating the longest assembly duration. Additional cases are also presented where the option is given to consider the open deck as an additional public space (case 5) or to analyze the travel duration from assembly station to the entry point of LSA (case 6). Case 6 should be taken into account if separate embarkation and assembly stations are employed. The arrangements should be modified if the total evacuation duration, see Figure 2.1, does not comply with the allowed duration, in order to make the design comply. Additional information for each method is given below.

The simplified method is explain in Annex 2 of MSC.1/Circ.1533, a short method explanation will be given here. The routes, corridors and stairways are modelled as a hydraulic network. The pipes are corridors and stairways whereas the doors are modelled as valves. There are 5 specific assumptions given. First, all passengers simultaneously start evacuating. Second, walking speed depends only on the density of people and the flow always moves in the direction of the escape route, also there is no overtaking. Thirdly, persons move unhindered. Fourthly, counter flow is not modelled and is taken into account with a counter flow correction factor. Fifthly, additional simplifications are taken into account using a correction factor and a safety factor. For the simplified method the congestion criteria is 3.5 persons per m^2 or greater, and difference between inlet and outlet flows is 1.5 persons per second. For the advanced method the congestion criteria is 4 persons per m^2.

The guidelines on how to perform an evacuation analysis refer to the Fire Safety Systems (FSS) code to determine the initial distribution. Below the regulation part regarding distribution of persons as described in chapter 13: Arrangement of means of escape [13]. Case 2 is taken from resolution MSC.410(97) which will go into force on 1 January 2020, similar with amendment MSC.404(96).

2.1.2.2.2 Distribution of persons

- *Case 1*
  Passengers in cabins with maximum berthing capacity fully occupied; members of the crew in cabins occupied to 2/3 of maximum berthing capacity; and service spaces occupied by 1/3 of the crew.
- *Case 2*
  Passengers in public spaces occupied to 3/4 of maximum capacity, 1/3 of the crew distributed in public spaces; service spaces occupied by 1/3 of the crew; and crew accommodation occupied by 1/3 of the crew.

2.1.2. Alternative Design Approach

An alternative design approach can be performed if the design does not meet IMO criteria. The alternative design report should provide proof that the design meets the fire safety objectives and reaches an equivalent level of safety. This approach is described in SOLAS chapter II-I:Construction - Structure, stability, Installations, II-2: Construction - Fire protection, fire detection, and fire extinction, and III: Life-saving appliances and arrangements. Means of escape is governed in chapter II-2 and thus the alternative design approach is elaborated upon in this section.

The approach stipulates that documents should be provided which described which part of the design is not meeting the criteria. This design part can be, for example, an area of a space in the ship. Next to this, the expected hazard and hazard properties should be defined. These describe in detail the possible ignition sources, fire growth potential, smoke and toxic generation, and potential spreading. For this system and hazard a required level of safety is defined which is of an equal degree of safety as the rules. The approach requires more time than the prescriptive based approach, however, the benefits could be having more options, cost effective design, and improved knowledge of loss potential [36]

A reference is given in II-2 for additional information to MSC/Circ.1002 which give guidelines on alternative design and arrangement for fire safety [3], [36]. For carrying out an alternative design, the design team should appoint a coordinator, communicate regularly with the Administration, determine safety margins, conduct a preliminary analysis in qualitative terms, conduct a quantitative analysis, and document each part.

Fire hazards should be defined in detail considering at least pre-fire situation, ignition sources, initial fuels, secondary fuels, extension potential, target locations, critical factors, and relevant statistical data. The fire hazards are grouped in three incident classes, namely: localized, major, or catastrophic. Which consist either of a fire limited to a specific area, a fire limited to the ship boundaries, or a fire affecting also the surrounding ships or communities. Risk can never be completely eliminated and designers performing the risk assessment should keep this in mind [36]. One aspect of the analysis is to define performance criteria. The evacuation time can be amongst the criteria which need to be assessed.

2.1.3. Code of Safety for Special Purpose Ships, 2008

The Code (SPS) provides international standards for special purpose ships. The definition of a special purpose ship is that it is a mechanically self-propelled ship which by reason of its function, carries on board more than 12 special personnel. Below are some rules taken out given an example when a special purpose ship is treated as a passenger ship. An special purpose ship is not considered a passenger ship in general because of the assumptions stated in the preamble .4:

> *Special personnel are able bodied with enough knowledge of the layout of the ship and have received some training in safety procedures and the handling of equipment that they need not be treated as passengers.*

Chapter 6 references to SOLAS II-2 which contains the evacuation analysis regulation. In SPS chapter 6 it states that:

Chapter 6 - Fire Protection

- ***6.1 For ships carrying more than 240 persons on board, the requirements of chapter II-2 of SOLAS for passenger ships carrying more than 36 passengers should be applied.***
- *6.2 For ships carrying more than 60 (but not more than 240) persons on board, the requirements of chapter II-2 of SOLAS for passenger ships carrying not more than 36 passengers should be applied.*
- *6.3 For ships carrying not more than 60 persons on board, the requirements of chapter II-2 of SOLAS for cargo ships should be applied.*

Before amendment MSC.404(96), the SPS regulation referred to SOLAS II-2 where SPS ships should be seen as passenger ships. An evacuation analysis was only mandatory for ro-ro ships and such an analysis is not mentioned in the part for passenger ships. The change in regulations also makes it mandatory for Special Purpose Ships with more than 240 persons on board to perform an evacuation analysis. This is also stated in IMO [37] under §14.10.2: *"evacuation analysis to be mandatory for special-purpose ships carrying more than 240 persons on board"*.

2.1.4. Remarks

From IMO requirements, the criteria to perform an evacuation analysis is if either the ship is categorized as a passenger ship with more than 36 passengers, if it is a ro-ro passenger ship or if the ship is a special purpose ship with more than 240 persons on board. The International Code for Fire Safety Systems (FSS) has been reviewed but no evacuation simulation is described in this convention. Chapter 13 *Arrangements of means of escape* describes the required widths of stairways and hallways. The longest evacuation time from two cases (day and night) is used. The maximum capacity of a space is calculated by being either equal to the number of seats or similar arrangements or by assigning 2 m^2 of floor space to each occupant.

The IMO framework regarding the development of the process from hazard detection is depicted in Figure 2.2. Some flag state disagreed about taking trim and heel into account [38]. Which was either due to lack of statistical evidence on the influence on evacuation or that the loss of stability would only linearly affect the evacuation times. The focus of an analysis should be *"...identify congestion points and/or critical areas and to provide recommendations as to where these points and critical areas are located on board"* [39]. In other words, only take things you know into account otherwise you risk of deviating from the analysis goal.

Possible modeling requirements taken from regulations are to be able to:

- Analyze egress in early design stage
- Identify congestion points
- Demonstrate escape arrangements to be sufficiently flexible
- Identify areas of counter/cross flow

If the design does not meet IMO criteria than an alternative design approach is an option. Designers should provide sufficient proof that the design meets the level of safety and objectives required by IMO and FSS.

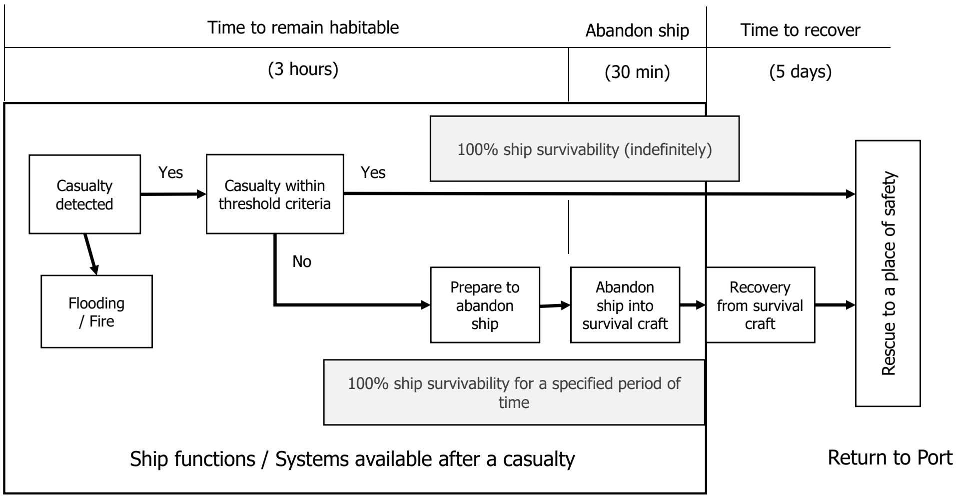


Figure 2.2: IMO framework - passenger ship safety. Adopted from [11].

2.2. Evacuation

To evacuate is to move people from a dangerous place to somewhere safe[1]. Different industries pose different environments and hazards and therefore have their own dangerous places and safe areas. Each type of hazard creates its own challenges which are different for each industry. Proper evacuation management is thus a basic requirement in safety concepts [40]. In the event of an emergency everyone present should be able to move safely from a hazardous location to one of relative safety. This should also be the primary aim of an egress system where the concept of relative safety is an important one [41]. Relative safety in the sense that it is in-feasible to design a perfect egress system which prevents everyone from being injured or killed [41].

This section will focus on different evacuation aspects in the building industry, fixed offshore installations, and maritime evacuations. In section 2.1 it became apparent that almost all the data and parameters in the guidelines on the evacuation of ships are based on data derived from the civil building experience [16]. Kobes *et al.* [42] also confirmed similarities between ship evacuations and building evacuations. The most noticeable differences being the ships motions which come into play.

Fixed offshore platform evacuation shares similar challenges to ship evacuations, since both operate in the same environment. The offshore industry deals with a high risk environment. Precautions can limit the chance that an emergency event will occur, however the consequences remain enormous. From the literature it became apparent that offshore industry focuses mainly on risk assessments and hence that is described in further detail. The building industry has a variety of different building types which is why different egress strategies are developed for different situations, for example one might consider the difference in difficulty between evacuating a hospital or a skyscraper.

2.2.1. Building industry

The ability to successfully evacuate in a dangerous situation in depends on the architectural layout and building components [42]. The characteristics of the layout and occupant demographics influences the egress strategy. An egress strategy is a plan that takes certainties into account when addressing uncertainties in order to attempt to achieve a desired outcome [41]. In the building industry egress strategies are, for example, protect-in-place, relocate to a safe place, phased evacuation, or simultaneous evacuation. This section will describe some of the egress strategies used in the building industry.

Protect-in-place strategies allow for occupants to remain where they are during an emergency. This strategy is applied to structures where occupants have a limited ability to move. It was developed after

[1]merriam webster

terrorists placed a car bomb outside a building and then sounded the fire alarm. Relocation to a safe area is a strategy where occupants are relocated within the building to a safe area. In some cases it is more effective to relocate a group within the building rather than to evacuate the entire building. These two strategies could be employed by hospitals or institutional facilities. Phased evacuation means first relocating occupants who are in immediate danger and letting other occupants who must, for the time being, remain in place. For high buildings this strategy is often applied. This strategy does not consider multiple simultaneous events instead it assumes that occupants outside the dangerous area are not affected. Simultaneous evacuation would allow all occupants to leave the facility at the same time during an event. Some of these strategies could also be beneficial in the maritime sector. Large cruise ships have diverse passenger demographics and hence care should taken with the evacuation strategy.

Next to these strategies, designers should also take into account people with disabilities and they should incorporate the movement limitations in the egress strategy. In Europe, 1 in 7 people report having difficulty with basic activity [43]. A basic activity can be lifting, standing, walking, bending, seeing, hearing, concentrating, or remembering. Design strategies that take this group into account fall into three categories. Either defend-in-place, allowing for evacuation through safe means (for example elevators), or implementing procedures to assist this group during emergencies.

An egress strategy can be developed from a prescriptive approach or from a performance based approach. A prescriptive approach uses a developed code and checks if the performance meets the code criteria. Due to the diversity of buildings and the occupant population, one universally accepted maximum evacuation time would not be logical. Therefore performance-based approaches were developed to assess hazards and to determine the maximum time available for occupants to evacuate. This analysis is more specific to a certain building design. Such an approach generally consists of 7 interrelated steps.

1. Identify project information
2. Identify goals and objectives
3. Develop performance criteria
4. Identify scenarios and select design scenarios and design loads
5. Develop candidate design options
6. Evaluate candidate design options and select a final design
7. Develop final design documentation

A performance-based approach can involve time-based egress calculations, this method is the one most commonly used. It involves developing a hazard and estimating the available time, assessing the response time of occupants to begin egressing and comparing these two times to determine whether the occupants can be safely evacuated. A key factor in this calculation is to determine when the environment becomes untenable, i.e. when it becomes incapable of supporting life. Therefore, untenable conditions need to be defined. These conditions are, for example, thermal exposure, inhalation of toxic products, and visibility limitations.

2.2.2. Offshore Installations

Evacuation, escape and rescue (EER) plays a vital role in protecting the lives of personnel in the event of a hazard on a fixed offshore installation platform. Most of the casualties in several offshore accidents occurred during the EER process[5]. The objective of the evacuation system is to leave the installation without directly accessing the sea, whereas escaping is the process of leaving the installation when the evacuation system has failed [11]. The general stages of an offshore evacuation are described in Methodology for Hazard Identification on EER Assessments by Health and (HSE) [12], and they can be seen in Figure 2.3.

Espen *et al.* [5] describe the influence that risk influencing factors (RIFs) have on EER operations. Here, an RIF is defined as *"an aspect (event/condition) of a system or activity that affects the risk level of this system or activity"*. The authors accomplished this by reviewing the Deepwater Horizon EER operations during the disaster of 20th April 2010 and using research obtained from the building industry, since these industries share similarities regarding fire hazards. Including the human behavior in modeling EER processes for offshore installations tends to be difficult due to the lack of research

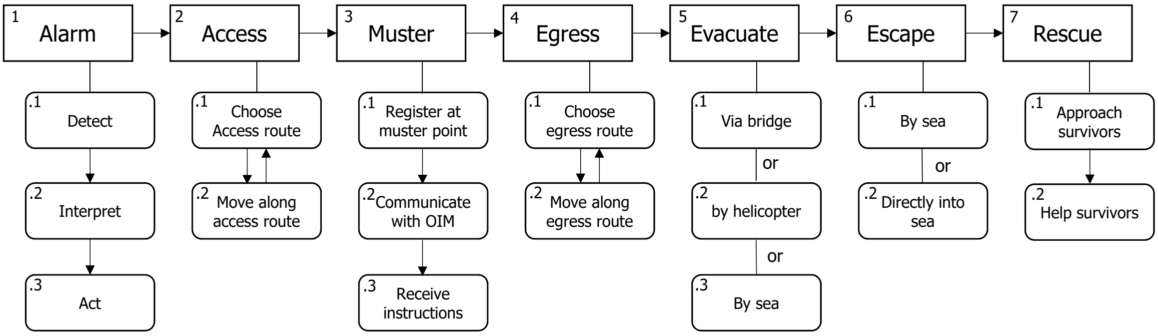


Figure 2.3: EER process, as defined by Health and Safety Executive [17]

data available [5].

Hazards on offshore installations can mainly be divided into three categories: physical hazards, command and control hazards, and behavioral hazards. These are due to equipment and physical conditions, poor procedures, protocols and communication, and hazards attributed to human factors [44].

Human and organizational factors are composed of human factors, which is a range of human characteristics that influence behavior, and organizational factors, which are characterized by the tasks of personnel, training, protocols and the like. The influence of design is itemized under the installation RIFs. These factors are, for example, layout, materials, the size of the installation, the distance to the muster area, the complexity of escape routes, equipment passed, and the protection of the muster area. Hazard RIFs depend on the type of hazard and the characteristics affiliated with it as well as the influence of the hazard on human perception. The hazard can create an untenable environment.

2.2.3. Marine industry

A maritime evacuation starts when the alarm has been sounded and continues until the last person is safe. The evacuation process is very complex [11] and it is difficult to evacuate occupants from an enclosure [4]. Figure 2.4 shows the overall process including activities performed by crew. Rescue operations are not included in the process depicted in Figure 2.4 and this only shows the ship-related evacuation activities and the lifeboats-related activities.

The above figure gives the overall marine evacuation process. However, from a passenger point of

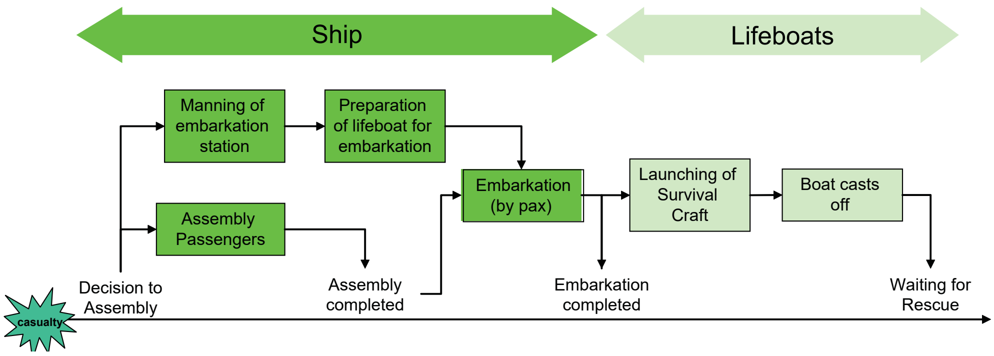


Figure 2.4: Marine evacuation process, copied from [11, Ch.2, p. 54].

view, this process can be divided into two distinct stages, the mustering stages and the abandonment stage [4]. The mustering stage consists of mustering all passengers at the designated areas on board. From there the passengers can enter the lifeboats, that is defined as the abandonment stage. Glen and Galea [4] describe the evacuation process as the following enumeration of events, this list shares a similar structure to that described in Figure 2.3.

Mustering phase
1. Reacting to the alarm
2. Deciding where to go
3. Retrieving life jackets
4. Getting to the muster stations

Abandonment phase
1. Moving as a group to an abbandonment station
2. Deploying life saving appliances
3. Abandoning the ship

Rescue follows after the mustering and abandonment phase. The entire process is also influenced by the behavior of the passengers on board. It is very complicated to predict human behavior during an evacuation [6]. Currently such human behavior is modelled through variation in human attributes such as walking speed, gender or age, Nevalainen *et al.* [6] consider human behavior by studying the cognitive process of a person to try to understand the decision-making process.

Reacting to the alarm during the mustering phase depends on the day part. IMO stipulates this to be 5 minutes during the day and 10 minutes during the night [24]. Evacuation delays due to reaction time can be attributed to alarm recognition, assessment of relevance, threat recognition, need for information and orientation, and commitment to other tasks. Three types of behavior can be observed after evacuees hear an alarm. Either the evacuee waits for further instructions or for other people to act, searches for additional information to assess the situation, or he starts to evacuate immediately [45]. Human behavior has not been considered in this research due to the complexity of the matter.

Most emergencies on board ships can be classified in six groups [46]. These emergencies occur in the casualty block in Figure 2.4. More specific emergencies can then be specified under one of the these main categories. The literature found on evacuation mainly starts with fire being the initial hazardous event. The six categories are:

1. Fire
2. Damage to the ship
3. Pollution
4. Unlawful acts threatening the safety of the ship and the security of its passengers and crew
5. Personnel accidents
6. Cargo-related accidents
7. Emergency assistance given to other ships.

The evacuability of a ship is defined as the evacuation performance capability [11]. Evacuability includes factors that influence evacuation performance. The term is a function of a set of initial conditions and evacuation dynamics. These initial conditions depend on the environment, the distribution of passengers, and the awareness time. The evacuation dynamics describe the speed of movement of passengers which is again a function of gender, age, mobility impairment, ship motions, and the overall well-being of the evacuees. Factors influencing the evacuability are listed below with the initial conditions and evacuation dynamics in the main categories and the respective sub-factors influencing these main components listed below.

- Environment (env)
  - Geometry
  - Topology
  - Semantics
  - Scenario
- Distribution (d)
  - Location of people
- Crew
  - Controlling spaces
  - Searching
  - Reducing Los Pax
  - Re-routing
- Awareness Time (r)
  - Initial Reaction Time
  - In-situ Reaction Time
- Speed (s)
  - Gender
  - Age
  - mobility Impairment
  - Ship motions
  - Well-Being

Evacuability is a function of the variables as given in the function [11],

$$E = f\,(env, d, r(t), s\,[evacplan, crewfunctionality, mobilityimpairmentindex]\,; t) \tag{2.1}$$

Not all of the above points are available in early ship design. This design stage does hold the greatest potential for improving safety [11]. Personnel movement on board a ship is strongly related to layout design or, more specifically, to the physical arrangement of the ship. Issues related to personnel movement are addressed after ship layout has been finalized and thus this issue can be investigated within the finalized design constraints. This results in an inefficient solution to the personnel movements [47].

2.3. Design

2.3.1. Early stage layout

The ship design process can be subdivided in distinct stages. Droste *et al.* [48] identifies three major stages: early stage ship design, contract design, and detail design. Only the first stage evaluates different designs whereas the latter two stages focus on a single design. The duration of each stage varies with ship type and ship complexity. Not all ship design follows the same process [49], and therefore only a general description of the early stage characteristics will be given. The latter two detail stages are out of the scope. The choice to focus on the early ship design stage is due to the design freedom. This stage is characterized by a still fluent ship design where decisions have major impact on the ship process and final result [2]. An estimated 90% of the decisions which have major impact on final design have been made in this stage. Later in the project decisions cause design lock-in. Design lock-in implies that design aspects are fixed and unchangeable.

The early stage can be again subdivided in different sub-stages. Andrews [50] identifies three distinct sub-stages for warships which are concept exploration, concept studies, and concept design. van Oers *et al.* [51] describes two distinct sub-stages, used by The Netherlands Defence Material Organisation (DMO), which consists of an A-phase (concept exploration) and B-phase (concept definition). Both approaches are used for the design of complex naval warships and are an example how different instances define different design process stages. Both approaches start with exploring the solution space considering initial requirements, then identify design options to further investigate impact of design choices on ship function. And lastly, ensure that sufficient design information is gathered to justify proceeding to the contract stage. The process where requirements are evaluated throughout the early stage and are updated according to new gained information is termed Requirement Elucidation by Andrews [49]. A critical aspects of the previous three stages is to keep evaluating the functionality of the requirements and whether or not they should be adjusted.

It should be noted that previous described ship design process is also affected by the ship type and level of novelty. [49]. There can be considerable difference between the design process of a specific innovative ship design and large serie transportation vessels [2]. An evacuation analysis has to be performed for both highly complex ships, such as large cruise ships and special purpose vessels (having more than 240 special personnel on-board), and smaller less complex ships such as smaller ferries. It is considered impractical to perform a review of all design-models, -tools, and -methods applied to the various ships described. Nevertheless, the early design stage for all vessels coincides with the most design freedom and hence design decisions made during this stage affects the final evacuation performance or evacuability. It is therefore of interest to further capture early stage ship design aspects.

The relation between design freedom and the different project stages is depicted in the Figure 2.5. The total cost and knowledge of the problem increase while design freedom decreases. Choices in physical layout are made during the early design stage and physical layout relates closely to egress performance. The physical layout aspects which influence egress performance are elaborated in this section.

The layout of a vessel is a function of the ship type and purpose. The type and purpose of a ship determines the amount, location, and function of the spaces. Ship design varies per ship type and

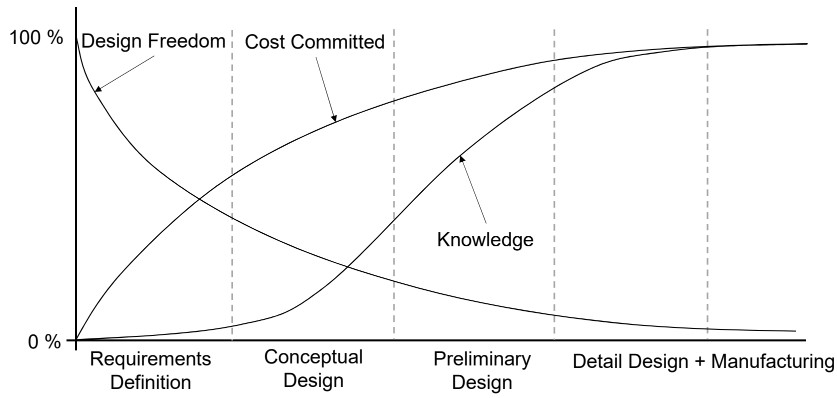


Figure 2.5: General design characteristics, from Cooper *et al.* [1]

hence categorizing can help understand design impediments [49]. For passenger ships the compartment type or function can be either that the compartment is used for passenger purposes or crew purposes. Passenger purpose compartments are, for example, cabins, theaters, discos, casinos, and accommodation. Crew purpose compartments are machinery spaces, galleys, bridge, crew cabins, and the such. Passenger ships are configuration-driven ships where the layout configuration dominates the vessel performance [48]. The layout of special purpose vessel vessels composes of cabins, variety of work stations depending on ship function, workshops, recreational spaces and more. The geometrical and topological features of the compartments affects the initial population distribution. The compartment type can also have influence on the response time of evacuees [23], for example, the crew could have a delay due to safe work termination protocols whereas passengers in cabins do not.

As previous described, designers should decide the compartment configuration based on requirements and the ships function. The general arrangement design of a passenger, cruise, or ferry ship starts with the choice in location of public spaces and cabins [52]. As such, decisions made regarding the space locations affect various design characteristics, such as weight distribution, population distribution, evacuation performance, access, and so on. This concept is termed ”style” by Brown and Andrews [53] and can be defined as:

> *”the combination of whole ship performance metrics and local system metrics, grouping information form different domains to enable the inclusion of ill-defined knowledge.” [52]*

Thus style captures overall design characteristics and properties, examples of style are configuration, robustness, operability, sustainability, survivability, and so on. Improving survivability has influence on a range of design aspects such as number of bulkheads, layout configuration, defense systems, and more [52]. One suggested style is evacuability, defining this as a style has not been encountered in literature read. Improving the evacuability of a ship will affect a range of different design features, such as compartment geometry and topology. Casarosa [15] does include *personnel movement* as a design style which is similar to evacuability, except also considering normal operations instead of only focusing on an emergency scenario. Two studies which focus on the influence of a design configuration on evacuation performance are highlighted below.

The fire safety engineering group at the University of Greenwich, in collaboration with University College London, conducted project EGO in the 2005-2007 period [54]. This project explored the interface between design issues and crew numbers, functions, and movement issues. This was achieved by connecting the design software PARAMARINE-SURFCON with maritimeEXODUS. The two designs are given in Figure 2.6 and were compared using a human metric indicator. The analysis was made on a naval combatant with 262 crew. A difference in performance was shown between the two designs. The designs were evaluated using a Human Performance Metric (HPM). In this case the HPM was calculated using a range of evaluation criteria. The evaluation criteria contained both evacuation scenario criteria and normal operation scenario criteria. Their study concluded that one single centralized passageway performed better than two parallel passageways.

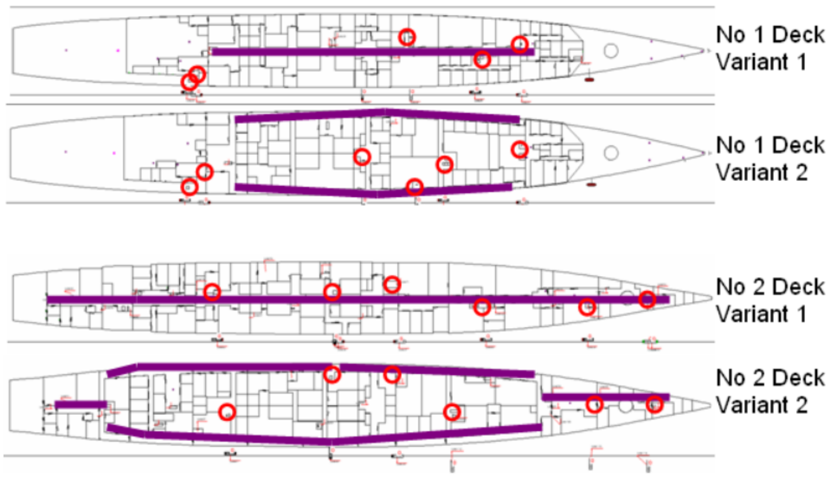


Figure 2.6: Two naval vessel layouts, copied from Casarosa [15]

Choosing the location for exits also influenced evacuation performance. Passengers have to decide which exit to use when they can choose between multiple exits. Generally, they tend to choose a familiar exit or follow other people [14]. An imbalance in exit options can cause overcrowding or congestion. Kurdi *et al.* [14] examined the influence of exit placement on evacuation in a congested environment. Four different arrangements were created: exits on one side, exits on adjacent sides, exits on opposite sides, and exits on all sides. The outcomes were then compared to evaluate each setup in terms of evacuation performance. The authors used a 17x20 square grid where occupants could move in four directions. Each grid had a size equal to one square meter, each agent could only occupy one grid node and the speed of agents was 1 ms^{-1}. An evacuation strategy was devised using both simulated annealing and Depth-first search to calculate evacuation times. Using the depth-first approach it was concluded that placing exits on adjacent sides of beneficial for evacuation performance. This approach more closely coincided with pedestrian evacuation in dangerous situations. Both Kurdi *et al.* [14] and Casarosa [15] will be used for validating the MDP model.

2.3.2. Layout and safety

Ahola *et al.* [55] identified five safety perception themes, i.e. how passengers perceive safety. The themes are life-saving appliances, communication, emotions, other people, and architecture. The availability of life-saving appliances, for example life-vests, lifebuoys and the such, contribute to a significant part of perceived the safety on board. Clear communication from competent-looking officers and other people creates an environment in which the passengers feel safe. Lastly, the influence of architecture, or the environment, is primarily perceived through the interaction between passenger and environment. This theme coincides mostly with the scope of the literature research and as such is described in more detail.

The passenger environment theme is subdivided in architecture and decoration cluster. The former is described as the openness of the spaces, transparency of the layout, and the vertical spaces. Passengers tend to feel more safe in large open spaces, such as the main lobby, than smaller spaces such as corridors. Which is contradictory with the actual safety of these spaces. Large spaces tend to be less safe than smaller narrow spaces. This is due to the fact that hazards spread more easily in large areas. Staircases and elevators had a large impact on the perceived safety due to these being thought of as impractical. Passengers thought the width of staircases to be too narrow causing congestion. Designers need to recognize critical properties of the layout and improve these to increase natural navigation in emergency situations [55].

The width and brightness of corridors have influence on the path passenger take during an emergency situation. Passengers prefer to choose a wider corridor over a narrow corridor. Similarly they choose a brighter corridor over a darker one. The brightness is a more dominant factor in route choice than width when combined [56]. Due to design restrictions of the width of corridors, Ahola and Mugge [57] researched the influence of vertical height of corridors on perceived safety.

These two influences, width and brightness of corridors, are researched without taking a ship heel into account. As one can imagine, inclined corridors also influence movement speed and the decision making process of passengers. A summary of research on the influence of deck inclination on movement speed of passengers is given by Meyer-König [31]. Not all angles of inclination have been tested during safety of participants. No significant change in evacuation duration is calculated up to 15 degrees of inclination [31]. Critical deck slopes range between 14 and 39 degrees [58].

2.4. Modeling

This section describes different computer software used for modeling evacuation on ships. First three general descriptors are given which apply to simulation and models in general. Since most literature found on ship evacuation model uses a more specific categorization criteria, these will follow. The purpose of being able to describe a model from different perspectives will help to get a better understanding of all models [7].

The three descriptors given by Sokolowski and Banks [7] are scale, fidelity and resolution. Scale is the size of the modeled event with respect to space and time. Resolution is the level of detail of the space, for example amount of grid nodes with respect to the size. Resolution tends to decrease when scale increases due to computer limitations. Fidelity describes how closely the model resembles reality. A model with a high fidelity will resemble reality more closely compared to a model with a low fidelity.

Certain decision has to be made when developing a model[18]. Some of these decision descriptions are given in Figure 2.7. It should be noted that these decisions descriptions are not necessarily absolute, ie. either fully microscopic or fully macroscopic model. Figure 2.7 gives an overview of properties of models explained in this chapter. Some of the model decisions in Figure 2.7 return in literature on evacuation modeling. The main descriptors in marine evacuation literature are microscopic or macroscopic models. Microscopic models then either utilize a discrete method or continuous method to model agent movement. Evacuation models are often characterized based on the resolution. A model with a

specific	⟷	general
model estimation	⟷	first principle models
numerical	⟷	analytical
stochastic	⟷	deterministic
microscopic	⟷	macroscopic
discrete	⟷	continuous
qualitative	⟷	quantitative

Figure 2.7: Model decisions from Gershenfeld [18]

low resolution is called a macroscopic model, if the model has high resolution it is called a microscopic model. In order to model each individual in a microscopic model, one has to define the environment as small discrete geometric elements [11]. A mesoscopic model would have sub-models with different resolutions. Mesoscopic models are a combination of microscopic modeling at low level and macroscopic modeling at high level. At the low the level the interaction between agent and environment is defined whereas at high level the planning of routing is determined [11, 32].

In many of the literature on ship evacuation models the fidelity, scale and resolution criteria are not mentioned and the models are grouped according to the term microscopic, mesoscopic and macroscopic models [11]. Guedes Soares *et al.* [11] and Łozowicka and Czyz [10] both define these three categories. Boulougouris and Papanikolaou [9] in addition describe regression-based models, route-choice models and queuing models. Kostas *et al.* [8] categorizes crowd motion models on three approaches, based on a fluid model, based on cellular automata model, or based on a particle approach.

Macroscopic modeling composes of a graph network where arcs represent distances between points. This method models the ship layout as a hydraulic network where corridors represent pipes, doors represent valves, and compartments represent tanks [10]. Gas-kinetic models use a gas analogy and describe how the flow density and velocity change over time [9]. Microscopic modeling takes each occupant into account and models the movement of all occupants [10]. Microscopic models are then subdivided in social force models and cellular automata models. The difference is that cellular automata models are discrete models whereas social force models are continuous. The social force model consists of a set of definitions how people interact between each other, or more specifically define forces to describe the attraction, repulsion, or acceleration of the agents. These forces define the social field surrounding an agent which mimics a person's internal motivation to react to another person.

Three other type of models are described by Boulougouris and Papanikolaou [9], regression models, queuing models and route-choice models. Regression models predict occupant flow using relations between flow variables. Route-choice models use utility maximization to describe occupant movement between nodes. Queuing models use a markov-chain to describe occupant movement between nodes.

2.4.1. Building evacuation models

Gwynne *et al.* [59] analyze 16 computer simulation models used in the built environment to model evacuation. At the time being, 6 were still under development. A distinction can be made by the fundamental approach used by the models. The models can be distinguished by their approach and level of sophistication. Three fundamentally different approaches are identified, namely, an optimization approach, a simulation approach and a risk assessment approach. Optimization models (2 out of 16 models) assume that occupants will evacuate in the most efficient manner possible. They do not take non-evacuation activities into account. Simulating models (12 out of 16 models) do take individual behaviour and movement into account and they try to realistically model the agent's movements. The last group, the risk assessment models (2 out of 16 models), first identify hazards and attempt to quantify the risk. By repeating the calculations, one can statistically assess the variations in the risk.

The models are also distinguishable from the point of view of how they translate the design into a grid network. The nodes either represent a small area (fine grid) or a compartment or corridor (course grid). It is the choice of grid density that determines whether the model is able to capture individuals or only groups. Similarly, the models can either define the population from an individual perspective or from a global perspective. The former allows the designer to assign attributes to each individual. These attributes then influence the decision-making process and therefore also the movement. The global perspective defines a population without considering each individual and limits its capability to capture effects which influence individual occupants.

The decision-making process of each individual or group is governed by choice in the behavioural system. Five different systems are identified which define the behaviour of the occupants. One can have no behavioural rule system, a functional analogy behavioural system, an implicated behavioural system, a rule-based behavioural system or an artificial intelligence-based behavioural system. These different systems determine the individual and/or population responses throughout a simulation. They furthermore determine the interaction between people-people, people-structure and people-environment. This interaction occurs on three different levels: psychological, sociological and physiological. It is a response based on the attributes of the individual, on the interaction between individuals or the response is based between an individual and his environment. All in all, the modeling of human behaviour is complex and to date no model has been able to precisely capture the human behaviour.

2.4.2. Marine evacuation models

Each model has four general components which need to be defined [4]. These are configuration, environmental, procedural and behavior aspects. Configuration is the translation from layout to model and within this category the layout is defined. Environmental aspects contain all hazards and how they develop. Procedural aspects cover personnel procedures and define the knowledge of the passengers with respect to the layout of the ship. Behavior aspects defines how passengers react to stimuli. The models described in this section use different methods to adress these four aspects. An example of evacuation models used in the marine industry are maritimeExodus, EVI, ODIGO, EVDOMON, NMRI evacuation simulator, IMEX en AENEAS. A short description of maritimeEXODUS, NMRI evacuation simulator, EVI, and ODIGO are given below.

Glen and Galea [4] describes challenges in evacuation modeling and expands on an already developed evacuation model, EXODUS, to be also suited for ship evacuation analysis. The new model, maritime-EXODUS is developed by the University of Greenwich. maritimeExodus is a multi-agent based model which consists of five sub-models governing different aspects of the evacuation. These are a passenger, movement, behavior, toxicity, and hazard sub-models. The motion of each occupant is determined by a set of rules of which many are stochastic based. This results in a slightly different outcome each time the simulation is run [29]. maritimeEXODUS is a microscopic model where the layout is discretized into a two-dimensional grid.

The National Maritime Research Institute (NMRI) evacuation simulator composes of three sub models, a space model, evacuees model and disaster model. The space model defines configuration aspects and is a microscopic model. The evacuees model defines the procedure and behavior aspects and does this using a social force model to define the interaction between agents. The environment aspects are defined in the disaster model of the NMRI evacuation simulator and can influence the walking speed based on the outcome of a computational fluid dynamic (CFD) code [60].

The evacuation model EVI is a multi-agent mesoscopic model. It uses a social force model at microscopic level to define interactions between agents, and the wayfinding process is modelled at macroscopic level. The wayfinding is done through a graph representation of the ship layout from which edges of the graph can be influenced to represent a hazard spreading. The agents can be categorized within different groups, such as passengers or crew, these groups can then been assigned objective to influence the movement patterns. The objectives are, evacuate, return to cabin, go to a specific location, search cabins and assign an alternative route. The hazard spreading information for example is initially not given to the passengers and instead the crew is given the objective to re-route [32].

Boulougouris and Papanikolaou [9] explain the workings of the EVDEMON model, which is a multi-agent based cellular automata model. The layout is divided into cells of approximately 40x40cm^2. Each cell can either be occupied or not and passengers can then move in 8 directions. The speed is determined by limiting the amount of cells an agent can move each time step. The way-finding method is based on A* algorithm instead of a shortest path method.

Kana and Singer [12] and Kana and Droste [27] proposed an evacuation analysis tool using a ship-centric Markov decision process framework. The method makes use of eigenvalue and eigenvector spectral analysis to assess policy variations. First, the bellman equation is solved using value iteration to generate series of policies. The authors then create a new transition matrix by selecting the optimal policy for each epoch. By performing spectral analysis on the resulting matrix a better understanding is gained of the dynamics of the modelled system. This thesis expands on these two research papers.

2.5. Problem summary and method proposal

Recent IMO regulatory changes result in more vessels having to perform an evacuation analysis. In addition to ro-ro passenger ships, all passenger ships with more than 36 passengers and special purpose ships with more than 240 special personnel need to analyze evacuation. There is a notable difference between passengers and special personnel. The latter are occupants presumed to have enough knowledge of the ship layout and safety procedures. Either population affects the evacuation process, which

is of importance to the safety of those on-board. Therefore, it is of interest to a designer to evaluate the ship layout from an evacuation perspective. Early ship design holds the most design freedom and changes in layout are more easily implemented during this stage. This stage also coincides with a general layout and detailed information is not yet available. For these reasons, a method which is able to evaluate the design from an evacuation perspective using limited information is needed.
Simulation can help capture essential features of real-life applications which evolve over time and are highly complex. To simulate is defined in Jensen and Bard [61] as:

> *"to duplicate the dynamic behavior of some aspect of a system by substituting the properties of another system for the critical properties of the system being studied."*

There is always some degree of uncertainty involved in real-world systems [7]. A ship evacuation is similarly governed by uncertainties which result in different outcomes each evacuation. This is the reason why a deterministic multi-agent approach has to be run hundreds of times to ensure all possible outcomes have been calculated. Each evacuee has to make decisions in order to get to safety which are uncertain in nature. The combination of a stochastic system, sequential decision-making, and low information availability is the reason to evaluate if a Markov-Decision-Process model has potential to be used as an evacuation analysis tool.

A Markov-Decision-Process is used for a variety of purposes and in a variety of fields. It is used for queuing systems, search engines, manufacturing models, customer classification models, inventory models, and more. All of these uses share some common attributes. The processes are stochastic and a sequence of decision have to be made. The model can help understand how the system being studied behaves. Kana and Singer [12] and Kana and Droste [27] showed promise in using an MDP for egress modeling. This idea can be extending in creating a tool to help justify design decision and improve the safety on board ships.

3
Research method

The method which will be used to assess the design is a Markov Decision Process (MDP) and a Markov Chain (MC). In order to do this, the design has to be translated into something which can be used as input for the MDP. The layout has to be discretized into grid nodes which represents small areas. All these nodes are connected with each other, indicating how someone can move between them. For the following chapters the assumption is made that a person can only move in an: up, down, right, or left direction. This configuration is also used by Kana and Singer [12]. A grid node can at most be connected with four adjacent nodes, as a consequence of the directional freedom. A wall grid node is connected to no other node and therefore cannot be *'entered'*.

A Markov decision process is an extension of a Markov chain. Both of these methods involve a systems that transition between states. For example, a person can be located in a certain area, grid node, or state. For this thesis, the states are similar to the grid nodes described in the previous paragraph. The area is not taken into account in both an MDP as MC model. In other words, the size of a grid node is not represented by a size in state. Therefore, it is up to the designer to choose an appropriate size of the grid node. A second important concept in the two stochastic models are state vectors. These vectors represent how the system is distributed among the states. Or for an evacuation, how passengers are distributed among those states. The state vector indicates the probability of the system to be in a certain state. For example, a probability of 0.2 for state i would mean there is a 20% probability that the system is located in state i. For this thesis, it would mean that 20% of the population is located in state i. The method is probabilistic since no actual agents are simulated but probabilities.

A third important concept is transition probabilities associated with actions. For each state, the probability of moving to an adjacent state after choosing a certain action (up, down, left, or right) should be defined. The choice in probability highly affects the calculated results. Let the transition probability of successfully executing the most optimal action be 0.8. The most optimal action is given by the policies. This means that if the most optimal action *up* is chosen in state i, the probability of moving to the above state is .8. Or, 80% of the population in state i follow the most optimal route. During an evacuation not everyone follows the most optimal path towards an exit. Unclear instructions or panic can cause people to egress in a non efficient way. These transition probabilities represent this non-efficient behavior. The following section describes the two methods in more detail.

3.1. Markov-Chain

A Markov-Chain can describe how a stochastic system with different states changes. Such a chain consists of states and probabilities to move from one state to another. This thesis only considers Markov-Chain with a finite amount of states. The set of all states is called a state space. At each epoch, or time step, the system changes stochastically.The variables indicating the probability to move from state s_i to s_j are defined in the transition matrix M (Equation 3.1).

$$M = \begin{bmatrix} m_{11} & m_{12} & \cdots \\ m_{21} & m_{22} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} \tag{3.1}$$

For this example the probability is given by element m_{ij}. The size of this matrix is therefore nxn. Each row represents the current state and the each column represents the next state. The state vector s indicates the probability of being located in a certain state and is given by Equation 3.2. The initial state vector is denoted as s_0. Each row in M sums up to one, which is an Markov-Chain property. Similarly the sum of all elements in the state vector s sums up to one. The probability of being located in the next (time) step s' is then calculated by multiplying the transition matrix with the state vector (Equation 3.3).

$$s = \begin{bmatrix} s_1 & s_2 & \cdots & s_n \end{bmatrix} \tag{3.2}$$

$$s' = s\,M \tag{3.3}$$

3.2. Markov Decision Process

A Markov decision process is a Markov chain including actions and (discounted) rewards. Actions $A(s)$ can be chosen at each state. These actions result in gained rewards ($R(s)$). The transition matrix is denoted as $P(s'|s,a)$ and contains the probability of ending up in a certain next state s', after choosing an action a from a current state s. A short description of an MDP is given by [28], which states:

> *A Markov decision process is a sequential decision problem for a fully observable, stochastic environment with a Markovian transition model and additive/discounted rewards. It consists of a set of actions $A(s)$, states s with an initial state s_0, a transition model $P(s'|s,a)$ and a reward function $R(s)$.*

A sequential decision problem is a problem where the utility depends on a sequence of decisions. Utility is a measure of preference over a sequence of decisions. Fully observable states that an agent always knows where it is. And Markovian means that the probability of reaching the next state only depends on the current state. No previous sequence of visited states will change the probability of moving to the next state.

A solution to the above problem is called a policy. A policy is denoted with π, where $\pi(s)$ denotes the action recommended by policy π for state s. The optimal policy is denoted with π^*, which is a policy which yields the highest utility. The objective is therefore to find a policy which, if followed, yields the highest utility for a sequence of decisions/actions. A policy indicates the optimal action an evacuee should take to reach an exit. Policies are based on distance to nearest exit, discount factor, state rewards, exit reward.

To calculate the utility of a sequence one can look at the preceding states. This can be done by additive rewards, where the utility of a sequence equals the sum of all the rewards of the sequence states. A discount factor γ can be used when less value is placed on rewards received in the future. The utility of a sequence becomes a discounted version of the additive rewards when adding a discount factor γ.

- **Additive rewards**

$$U_h([s_0, s_1, s_2, ...]) = R(s_0) + R(s_1) + R(s_2) + ... \tag{3.4}$$

- **Discounted rewards**

$$U_h([s_0, s_1, s_2, ...]) = R(s_0) + \gamma R(s_1) + \gamma^2 R(s_2) + ... \tag{3.5}$$

The discount factor is a number between 0 and 1 and it determines how much value is placed on rewards gained in the future. A discount of 1 reduces the discounted rewards function (Equation 3.5) to an additive reward function (Equation 3.4). People tend to prefer rewards immediately over future rewards. For the model this means that immediate safety is preferred over future safety. Thus a discounted rewards function is used.

The set of decisions π and the utilities of a state s are given by Equation 3.6 and Equation 3.7 from [28]. The bellman equation states that the utility of a state is the reward of the current state plus the expected discounted utility of the next state. The assumption is that the optimal action will be chosen. The choice of policy is the argument of the maximum expected utility.

$$U(s) = R(s) + \gamma \max_{a \in A(s)} \sum_{s'} P(s'|s,a)\, U(s') \tag{3.6}$$

$$\pi(s) = \arg\max_{a} \sum_{s'} P(s'|s,a)\, U(s') \tag{3.7}$$

The bellman equation can be solved with a value iteration algorithm or policy iteration algorithm. For now, only the value iteration algorithm will be discussed. The value iteration initializes by setting the utilities of all states to zero ($U(s) = 0$). Then, the bellman equation is used to find the expected utility for each action. An intermediate step is done to create a quality matrix which calculates the utility per state per action. Lastly, the action yielding the maximum utility is chosen for each state. From these steps a new utility vector containing the maximum utilities for each state is created. This new utility function will be used for the next iteration, replacing the previous utility vector. This is iterated until the new utility vector barely differs from the previous utility vector. The difference between current and previous utility can be calculated and a threshold defined to end the loop [28].

3.3. Solution Markov Chain

The optimal policies indicate what an agent should do in each state in case the objective is to maximize utility. The rewards gained at an exit and lost at each state can be thought of as a level of safety. Hazards have a large negative reward and reduce the safety of occupants. Occupants are safe when an exit is reached, hence exit states contain a positive reward value. All other states contain a negative reward.

The MDP solution, consisting policies indicating which action to choose for each state, can be used to create a Markov Chain. Using the Markov Chain an simulation can be run indicating how the population evacuates. The same probabilities as used by the MDP are used by the Markov Chain, which denote the probability of moving in a certain direction. If in state s_4 the optimal policy is to move towards the adjacent state s_5 then the Markov Chain matrix has an element value of, for example, $m_{45} = .8$. This means that an agent in, for example, state s_4 will move with a probability of $.8$ towards state s_5. A different interpretation would be, if 100% of the population is located in s_4, then after one epoch 80% will have moved towards state s_5. This last interpretation is used in this thesis.

The action certainty value represents to what extend policies are followed. This is demonstrated with a simple $11x11$ grid where all policies point in the same direction. An agent has been placed in the middle state of one side of the room (1,5). The agent follows the optimal policies which point to the other side of the room. Figure 3.1 show the probability of an agent being in a state after some time. Only the probabilities of a single row is plotted, and the row which is plotted increases with each time. In other words, at $t = 1$ row 1 is plotted and at $t = n$ row n is plotted. The higher the action probability, the more likely an agent follows the optimal policies.

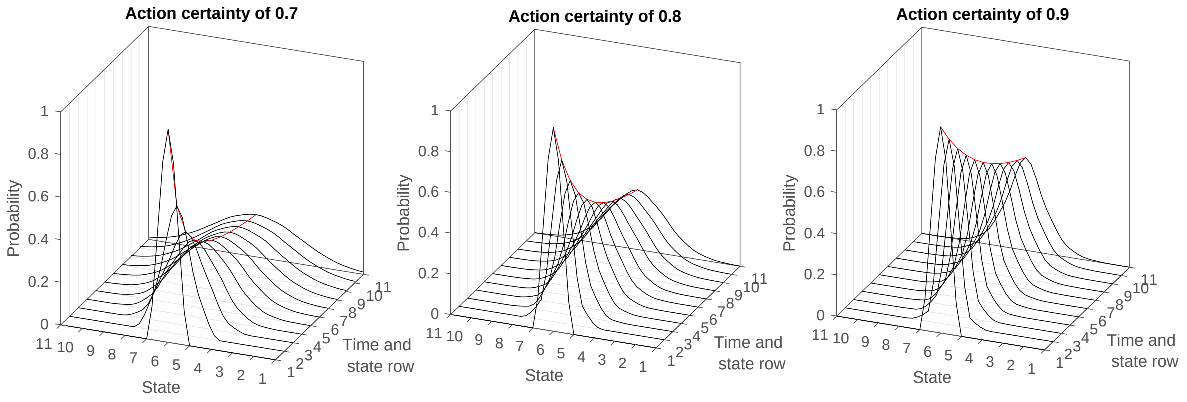


Figure 3.1: Influence of action probability variation on direction uncertainty of evacuee. The figure illustrates what the probability of ending up in a certain state is if the policy would be to move in a straight line. The red line indicates the policy direction. With an uncertainty of 0.7 the probability decreases each time step with 0.7 for the agent to remain heading in the most optimal direction.

3.4. Marine aspect of the MDP

3.4.1. Determining the initial distribution of an early ship layout

The FSS code can be used as a starting point to determine the initial distribution of passengers throughout the layout. To incorporate the regulation into the initial distribution, an estimate of the amount of passengers or crew is needed per deck, or a passenger-crew ratio is required. The latter would be sufficient because the MDP uses a probability distribution instead of a deterministic distribution of the population. Table 3.1 gives an overview of crew and passenger distribution as stipulated by FSS [13].

	Case 1		Case 2	
Space type	Passenger	Crew	Passenger	Crew
Public spaces	0	0	3/4	1/3
Accomodation	1	2/3	1/4	1/3
Service spaces	0	1/3	0	1/3

Table 3.1: Overview of FSS regulation regarding the distribution of persons for case 1 (night) and case 2 (day)

3.4.2. Translating layout to model

This section briefly explains how a layout is translated to a grid suitable for Matlab. An arbitrary layout is used for this section and the next, subsection 3.4.3. The layout does not need to contain detailed information because the model is used during early stage ship design. The layout used for the next example is the Pride of America Layout, found on the website of the Norwegian Cruise Line[1]. The MDP process, starting with a simple layout and ending with the optimal policies, is visualized in Figure 3.2. A short description for each step is given below.

1. A layout containing compartment locations and type, walls, and stairs is used. This layout is preferred to be an early stage layout. However, for this thesis a final layout is used because of the difficulty in obtaining an early stage ship layout.

2. A figure of the layout is loaded in Excel. An identifier is used for each cell within figure borders. These identifier determine the state properties. The identifiers and definitions are given in Table 3.2.

3. Matlab imports the Excel file and uses predefined numbers to identify each cell location and type. An additional Excel file is used for defining each compartment type. This is used to create the intial state vector.

[1] https://www.ncl.com/fr/en/cruise-ship/pride-of-america/deck-plans

Cell number	Definition
[empty]	Area each evacuee can be located in
1	Wall(s)
2	Exit state(s)
3	Hazard(s)
12	Service space
13	Public space
14	Accommodation

Table 3.2: Excel Cell identifiers

4. The MDP model calculates all utilities and policies for each state using the value iteration algorithm

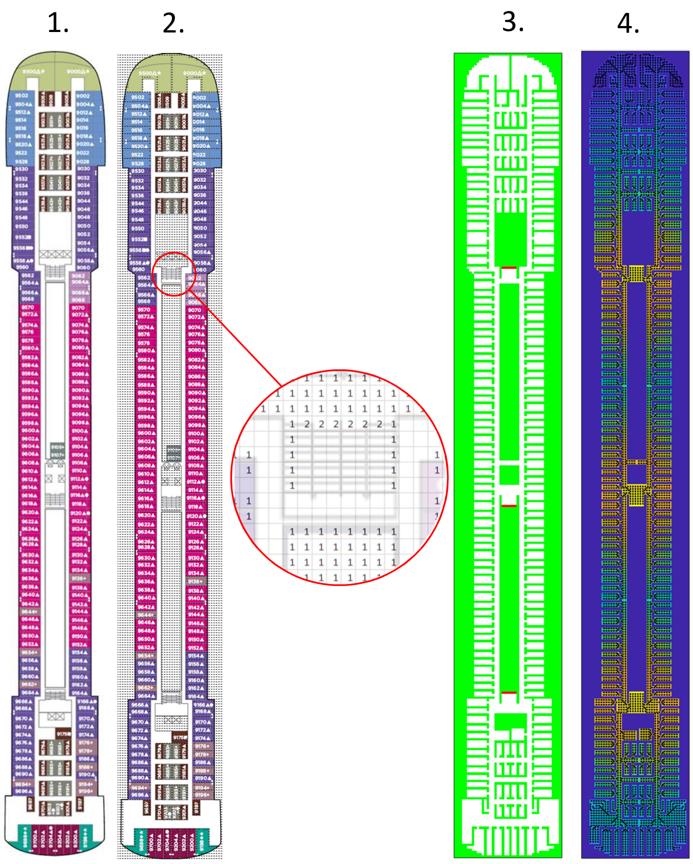


Figure 3.2: Intermediate Matlab model steps

3.4.3. Influence of scale on model complexity

Littman *et al.* [62] describes different methods of solving an MDP and explains the complexity of solving such a problem. The different solving methods (linear programming, policy iteration, and value iteration) are explained in more detail in the literature. The value iteration method is used for this thesis to solve the MDP. The Matlab code for the value iteration is provided in section A.3. The running time of this algorithm is a function of the amount of states and actions. The big-O notation is used to classify algorithms based on the running time. For the value iteration the running time for each iteration is $O(AN^2)$. The amount of actions A is kept at 4 for this thesis. The amount of states depends per layout and is thus the only variable influencing the running time per iteration.

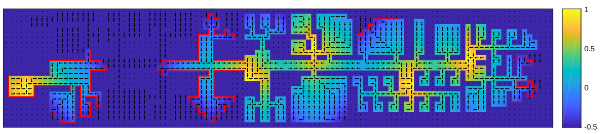
The running time and amount of iterations determine how long it takes to find the optimal policies. A way of stopping the algorithm is by applying a stopping rule. This stopping rule determines each iteration the residual between previous and current iteration. If this residual gets below a certain threshold, the iteration stops. However, for the thesis it was noticed that in order to compare utilities between different layouts the amount of iteration should be the same. Therefore, a maximum amount of epochs was chosen which ensured that the optimal policies were found, which is heavily influenced by the distance between the exit and the state furthest away.

For the following section the same layout is used as given in Figure 3.2 which was thought sufficiently large to verify an MDP capability to model a deck of a ship. The deck consisted of 6,275 states, excluding walls since these nodes would not be used. Matlab was used for the following calculations. Importing the deck and translating the Excel file to an array takes 4 seconds. The value iteration, with a maximum amount of iterations of 200 epochs, takes 193 seconds. The value iteration running time is proportional to the maximum amount of iterations. Regarding the memory usage, only 2.9 GB of memory was used of the 7.3 GB memory available. It was concluded that for this thesis the MDP model will be not computational intensive[2].

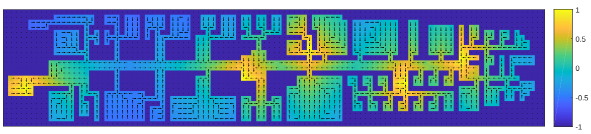
3.4.4. Choice of horizon

The amount of decisions an evacuee is given to reach an exit is also governed by the maximum amount of epochs the value iteration gets to calculate the amount of policies. If there is no fixed epoch limit or the value iteration is run until convergence, then the horizon is infinite. If only a limited amount of epochs is chosen limiting the value iterations ability to calculate the optimal policy, then the horizon is finite. Therefore the choice whether there is a finite or infinite horizon can influence the solution. For this thesis all simulations were performed with a infinite horizon. It does not matter how far you are located from an exit, eventually you will be able to reach one.

The algorithm was stopped when it was observed that the calculated optimal policies were not changing anymore. If this was not the case then some areas could not have *sensed* an exit and were therefore unable to determine which policy was best. Figure 3.3a gives an example with a finite horizon. The solution did not converge because of the amount of iterations was limited. In addition, the borders of areas which are solved are highlighted. These borders indicate the dividing line between policies leading to an exit and policies which do not. Figure 3.3b shows an example where the solution is converged. An infinite horizon is assumed because passengers tend to know where exits are located. This is due to evacuation drills on-board ships, evacuation plans, and general knowledge of a vessel. An infinite horizon means the iteration algorithm will stop when an optimal policy is found for each state. A finite horizon can be used to identify isolated areas.



(a) Example of solution with finite horizon, in this case 20 epochs



(b) Example of solution with infinite horizon

Figure 3.3: Example how the horizon choice determines whether or not all evacuees were able to reach an exit. Such a plot also can show which areas are difficult to reach. The color intensity denotes the utility values of each cell.

[2]Calculations were performed on a laptop with Intel i5-3210M CPU, and 8192 MB RAM.

3.5. Performance metrics

The following sections will further elaborate upon chosen metrics to evaluate the design. These metrics will be used to evaluate a design in validation studies in chapter 4 and chapter 5. The utilities and policies are a product of the MDP model. The utilities will be assessed based on the distribution and the policies are used for the Markov Chain simulation. From this simulation the time it takes for the population to reach an exit can be found. In addition, how the population is distributed among the exits can be calculated. Finding the maximum occurring probability for each state can indicate which areas are more likely to congest. Below, the utility distribution, exit usage, and maximum probability occurring plots are further clarified.

3.5.1. Utility distribution

The final utility distribution is used to determine the optimal policies. At each state, the optimal policy will indicate which action to take to maximize utility. The utilities are a function of the reward in the current state and a discounted expected utility in the adjacent state, as given by the Bellman equation (Equation 3.6). The rewards are the same for each state and are negative to create an incentive for an evacuee to move towards an exit, where a larger positive reward is given. The utility distribution can give insight in the effectiveness of a design, in order to compare different layout configurations. The mean μ is used to asses how well exits are distributed throughout the ship. A high mean indicates that on average each state is close to an exit. The standard deviation ω is used as an indication how many states are close to an exit.

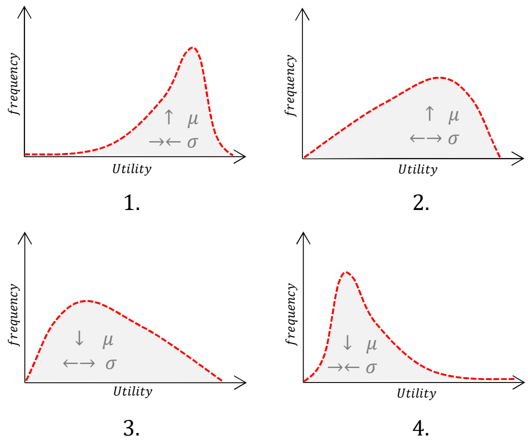


Figure 3.4: Four different utility distribution extremes. The number below each graph indicates the order of performance.

Whether a small or a large standard deviation is preferred, depends on the mean value μ. If the mean is high, then a small standard deviation means that many states are located near an exit. If the mean is low, then a small standard deviation means that many states are far away from an exit. The different combinations are given by Figure 3.4. The numbers indicate the order of preference. It should be noted that the initial distribution also affects how well exits are placed. Including the initial population distribution in the utility distribution plot would place more value on crowded areas close to an exit. This idea is further explained in chapter 8 but is left out of the scope of this thesis.

3.5.2. Exit convergence behavior

From the simulation the final population distribution among the exits is given. Plotting the state vector elements representing the exit nodes for each iteration gives a plot as given in Figure 3.5. Each of the three lines represents an exit. The steepness of this curve indicates how quickly evacuees *enter* an exit node. The difference between the exits converged probability indicate whether the population is equally spread over all exits. All exits consist of a single state, and hence share the same geometric properties. The figure can provide the naval architect with information regarding which exits are most critical.

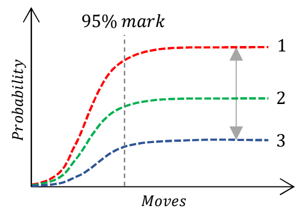


Figure 3.5: Example of the exit convergence plot.

Figure 3.5 indicates that exit 1 is most used and exit 3 least used. The sum of the converged values of all exist equals 1, or 100%. A 95% mark is given for the exit convergence plot to get a variable which can be used to compare different layouts. This mark indicates when almost all of the population has reached an exit. It could be that the last 5% represents the part of the population performing a search and rescue or a part of the crew performing a final sweep.

3.5.3. Maximum occurring probability

Concatenation of the state vectors for each epoch creates the Markov-Chain simulation matrix, as given Equation 3.8. Each row represents an epoch, each column represents a state. From this matrix the maximum occurring probability for each state can be found. This maximum value indicates the most busy, or congested, moment during the simulation. These values are found by taking the maximum value of each column in Equation 3.8. Plotting the maximum values can indicate where possible congestion occurs. An example of such a plot is given in Figure 3.6. This figure shows the top view of a deck of a frigate. The top figure shows the layout, where gray nodes indicate walls, white nodes are states, and red nodes are the exit states. From this figure it can be seen that, in this particular case, congestion will most likely occur aft of the two exits. The color bar indicates the percentage of the population located in a state.

$$M_{sim} = \begin{array}{rc} & \begin{array}{ccc} s_1 & \dots & s_n \end{array} \\ \begin{array}{r} epoch:\ 1 \\ epoch:\ 2 \\ epoch:\ t \end{array} & \begin{pmatrix} s_{11} & \dots & s_{1n} \\ \vdots & \ddots & \vdots \\ 0 & \dots & a_{tn} \end{pmatrix} \end{array} \tag{3.8}$$

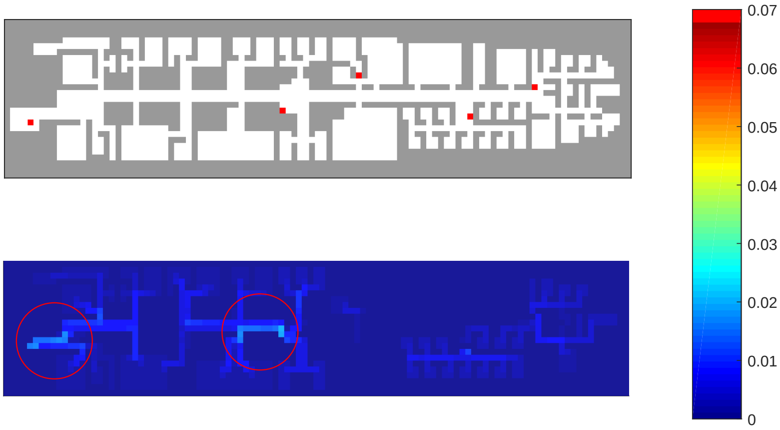


Figure 3.6: Example plot with the top figure indicating the layout, and the figure below plotting the maximum occurring probabilities for each state.

4

Validation study 1 : influence of exit configuration

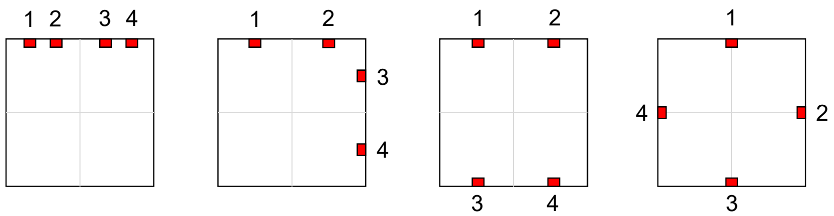
4.1. Goal

It can be of interest to a designer to vary certain design aspects and analyze the impact the variations have on the design performance. A measurement for performance could be, as also used in SOLAS, the evacuation time. Thus the influence of certain design decisions on evacuation time can be of interest to a designer. There is limited literature describing the relationship between the location of the exits and evacuation performance [14].

The previous chapter explained the MDP framework and how this can be used to simulate egress. This chapter will compare the MDP with a study done by Kurdi *et al.* [14]. The author evaluates, for a simple square layout, different exit configurations on evacuation performance. The goal is to validate the MDP methodology by comparing conclusion drawn on a simple layout with authors conclusions.

4.2. Paper summary

Kurdi *et al.* [14] analyzed the influence of exit location configuration on evacuation time and how the population is distributed among the exits. This was done using both a Depth-First-Search (DFS) as a Simulated Annealing (SA) method. The four layouts which were used are given in Figure 4.1. Each layout consists of a 17x20 grid and is divided in four quadrants. The width and height of each grid node is 1 meter, similar to the width of an exit. Two different population sizes were used, one with 50 pedestrians (N=50), and one with 100 pedestrians (N=100). Each individual had four actions to choose from, similar to the MDP framework. The simulations were run 100 times where each time the population was randomly distributed throughout the layout. For each simulation, four wall grid nodes were randomly placed throughout the layout. This was done to describes how pedestrians have to make a decision regarding an exit including obstacles in their way.



(a) One side (b) Adjacent sides (c) Opposite sides (d) All sides

Figure 4.1: Four different layouts created by Kurdi *et al.* [14], the red box denotes an exit. Four walls are randomly placed throughout the grid for each layout. Note: The layouts are not symmetrical.

The metrics used to evaluate each setup are the calculated evacuation time, and percentage of crowds at the exits. The evacuation time is calculated using the amount of evacuees using exit i (n_i), the width of the exit i, (K_i), and the speed of each pedestrian J_i, given by Equation 4.1. The percentage of crows at exits is calculated with Equation 4.2 using the amount of evacuees from exit i, and the total number of pedestrians N. Results show that the DFS method is able to model evacuation behavior more realistic than the SA method. Next, having exits on adjacent sides of the room performed, for both $N = 50$ and $N = 100$, worst. Locating the exits on all sides resulted in the best performance.

$$\frac{n_i}{K_i} + J_i \tag{4.1}$$

$$n_i \frac{100}{N} \tag{4.2}$$

4.3. MDP Results

In order to assess each layout, a Markov-Chain was created using the MDP policies (section 3.3). The initial distribution, as described in the paper, is used as the initial state vector. As described earlier, authors had to run 100 simulations with different population sizes in order to get realistic results. This is not necessary for the MDP model due to the ability to distribute an arbitrary large population evenly among the layout. This can be achieved by allocated to each state a population size equal to 1 divided by the state space size. The state space size equals $n = 17*20-4 = 336$. Therefore, this case assumes each state has a probability of being occupied by a pedestrian by one divided by total amount of states. The discount factor, which is kept constant for all calculations done in this chapter, is 0.9. This value influences the histogram which is used to assess exit location efficiency. Changing the discount factor would not affect conclusions drawn from the histogram. No variable discount factor was used because the objective is to the proposed methodology with existing research. The stationary MDP solution was used for to construct the Markov-Chain.

Let the desired direction probability be defined as a way of incorporating uncertainty in the behavior of an agent. This value influences if all agents move most optimally towards an exit or how much they deviate. This value is used to construct the MDP transition matrix $P(s'|s,a)$. It determines the probability of moving in the desired direction, see section 3.3 for a more detailed explanation.

4.3.1. Exit usage

Results are given in Figure 4.2, Figure 4.3, and Figure 4.4. Which are, in similar order, regarding the $N = 50$, $N = 100$, and $N = 336$ cases. These plots indicate how the population is distributed among the exits. If the lines are more close to each other, the exits are more evenly used. In Figure 4.4.b, exit 1 is most used. In other words, this design would place a higher toll on exit 1. To indicate when the majority of the population has reached an exit, a 95% threshold mark has been added for each plot. The layout with exits on all sides converges the fastest for each population size. Indicating that this design the most evenly and effectively placed exits.

An overview of the results is given in Figure 4.5. A short description of the results is given for each population size and method. The SA method has the least deviation between final exit population distributions. This method distributes the evacuees most evenly over each exit. Kurdi *et al.* [14] conclude that in real evacuations the population rarely is distributed evenly among the exits and that, therefore, the DFS method can simulate pedestrian movement more realistic. Regarding the $N = 50$ case, the difference between the MDP and other methods for this population size is the largest. It should be noted that the exits are not placed evenly across the sides of the layout. There are 3 nodes between the wall and exit 1, 4 nodes between exit 1 and exit 2, 4 nodes between exit 2 and exit 3, 3 nodes between exit 3 and exit 4, and 2 nodes between exit 4 and the wall. The amount of nodes between wall-exit1, exit1-exit2, exit2-exit3, exit3-exit4, exit4-wall for $N = 50$ is 4-3-2-4-3, whereas for $N = 100$ it is 3-4-4-3-2. Also, regarding the layout with exits on adjacent sides, for a population of $N = 50$, the amount of nodes between the wall and exit 1 is 4. Whereas for the population $N = 100$, it is 6.
There are similar deviations between the $N = 50$ and $N = 100$ cases for layout with adjacent sides, and also for the layout with exits on all sides. Thus no concise conclusion can be drawn between the

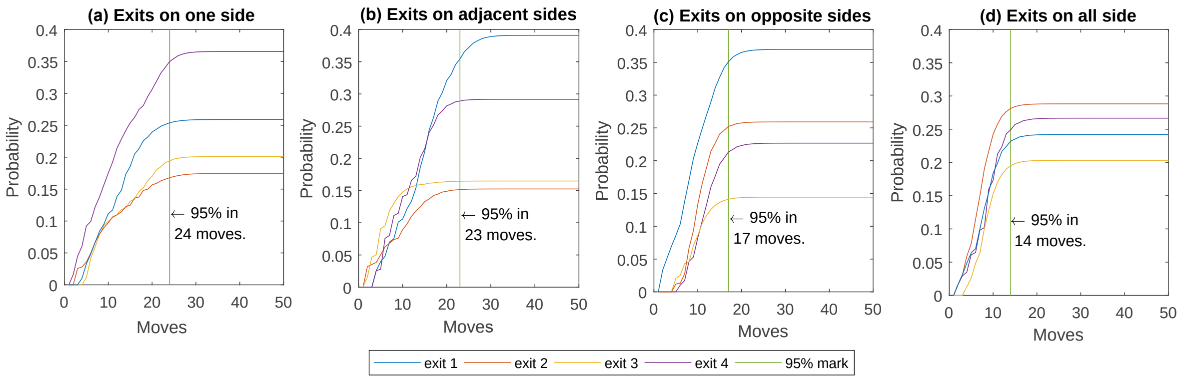


Figure 4.2: Exit convergence results for each layout for N=50

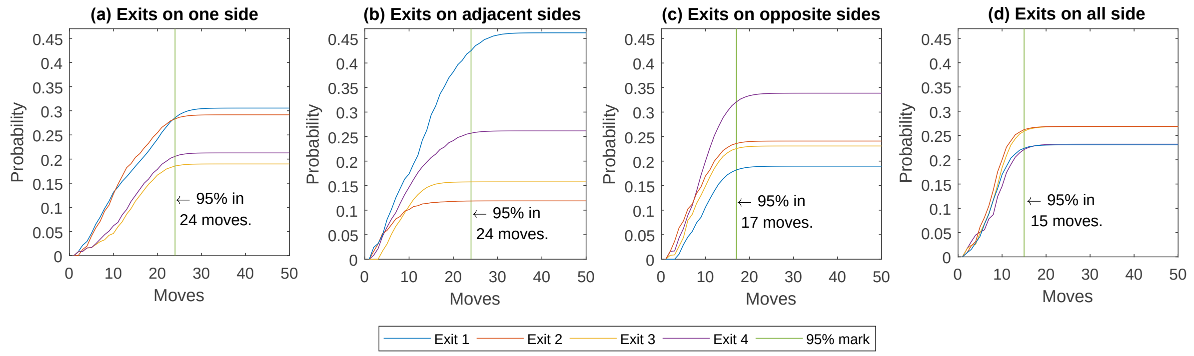


Figure 4.3: Exit convergence results for each layout for N=100

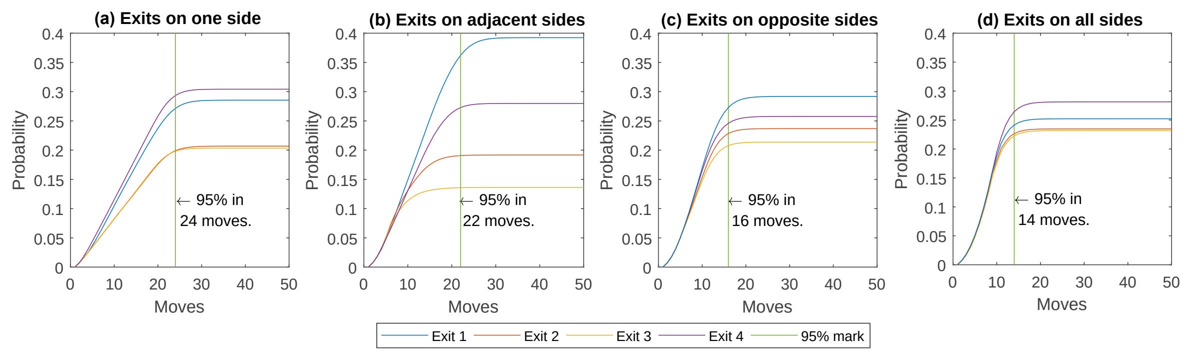


Figure 4.4: Exit convergence results for each layout for an evenly distributed population across the grid

$N = 50$ and $N = 100$ cases, since layouts were not similar. However, there can be still something said between the different layout types, in other words, which layout performed best.

4.3.2. Utility distribution

The layout are also evaluated by analyzing the MDP utility distribution, in addition to the exit analysis done above. The distributions are plotted in a histogram in Figure 4.6 including the mean and standard deviation per layout. The utility for each state is a function of the distance to an exit, the state rewards, and the discount factor. The rewards and the discount factor are kept the constant. Therefore, the utility will be a function of distance between the state and the nearest exit. The exits for the layout with exits on all sides, is most evenly spread out over the design. A high mean utility value is preferred, indicating the average state is in the vicinity of an exit.

N=50

	One				Adjacent				Opposite				All			
	Exit 1	Exit 2	Exit 3	Exit4	Exit 1	Exit 2	Exit 3	Exit4	Exit 1	Exit 2	Exit 3	Exit4	Exit 1	Exit 2	Exit 3	Exit4
SA	24.3%	24.4%	25.2%	26.0%	24.7%	25.5%	24.1%	25.6%	24.3%	25.7%	24.7%	25.4%	24.5%	25.2%	25.3%	24.9%
DFS	30.1%	22.4%	21.2%	24.3%	38.6%	16.0%	12.0%	33.5%	26.8%	23.6%	25.0%	24.5%	24.6%	24.0%	25.7%	25.7%
MDP	25.9%	17.5%	20.1%	36.6%	39.1%	15.3%	16.5%	29.2%	37.0%	25.9%	14.4%	22.7%	24.2%	28.8%	20.3%	26.7%

N=100

	One				Adjacent				Opposite				All			
	Exit 1	Exit 2	Exit 3	Exit4	Exit 1	Exit 2	Exit 3	Exit4	Exit 1	Exit 2	Exit 3	Exit4	Exit 1	Exit 2	Exit 3	Exit4
SA	25.5%	25.0%	25.9%	24.8%	24.8%	22.5%	24.4%	25.2%	25.0%	25.0%	24.6%	25.3%	25.5%	25.1%	24.7%	24.7%
DFS	30.2%	23.0%	23.0%	24.8%	41.9%	15.4%	11.6%	31.1%	27.6%	25.3%	22.2%	25.0%	24.9%	25.8%	25.4%	23.9%
MDP	30.6%	29.2%	19.0%	21.3%	46.2%	11.9%	15.8%	26.2%	19.0%	24.1%	23.1%	33.9%	23.1%	26.9%	26.8%	23.2%

N=332

	One				Adjacent				Opposite				All			
	Exit 1	Exit 2	Exit 3	Exit4	Exit 1	Exit 2	Exit 3	Exit4	Exit 1	Exit 2	Exit 3	Exit4	Exit 1	Exit 2	Exit 3	Exit4
MDP	28.5%	20.7%	20.4%	30.4%	39.2%	19.2%	13.6%	28.0%	29.2%	23.7%	21.4%	25.8%	25.2%	23.5%	23.2%	28.1%

Figure 4.5: Percentage of crowds at exit for each method and all layouts, table results.

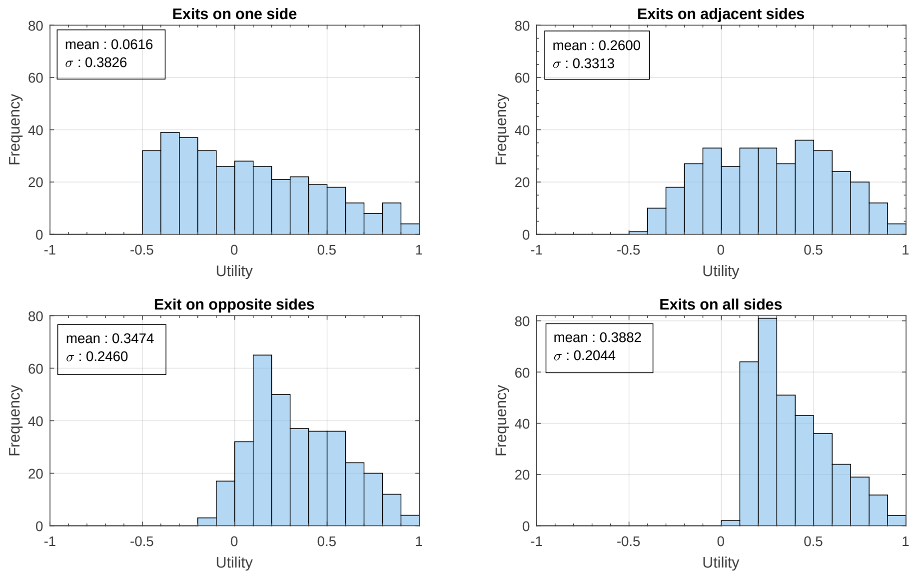


Figure 4.6: Histogram of the calculated utilities for each layout.

4.4. Conclusion

The DFS method will be used for the comparison since authors stated that pedestrians tend to adopt a DFS approach when choosing exits. It is therefore assumed that the DFS approach yields the highest fidelity. Having exits on all sides results in the smallest standard deviation of exit loads, for both population sizes. The standard deviation and the mean of the utility distribution is used to evaluate how evenly the exits are distributed, as explained in section 3.5. The layouts ranked from best to worst performance, based on utility distribution, is exits on *all sides*, *opposite sides*, *adjacent sides*, *one side*. The population distribution among the exits, for both $N = 50$ and $N = 100$, are given in Table 4.1 and are ranked from smallest standard deviation to largest standard deviation.

The DFS $N = 50$ and $N = 100$ rank layouts in similar order, the same order is concluded from the $N = 336$ MDP case. Only for the MDP $N = 50$ and $N = 100$ cases is the order slightly different. This is due to the MDP only simulating 1 out of the 100 population distributions, which was based on the example layout given in by [14]. The population was not evenly distributed throughout the layout for the example layout given by the author. The top left quadrant contains twice as many pedestrians as

Rank of smallest σ	N=50 DFS	MDP	N=100 DFS	MDP	N=336 MDP
1	All	All	All	All	All
2	Opposite	One	Opposite	One	Opposite
3	One	Opposite	One	Opposite	One
4	Adjacent	Adjacent	Adjacent	Adjacent	Adjacent

Table 4.1: Order from lowest standard deviation (1) to highest deviation (4). Indicating which design distributes pedestrians most evenly amongst the exits.

the bottom left quadrant for the layout with exists on opposite sides. Resulting in the majority of the population egress to exit 1.

Having exits on all sides always ranked best, having exits on adjacent sides always ranked worst. Since the MDP is an probabilistic method which does not need to model each agent/pedestrian individually, the $N = 336$ would give a similar solution as the 100 simulations done by Kurdi *et al.* [14]. The $N = 336$ case concludes the same as the DFS cases. In other words, a designer would come to the same conclusion (using the percentage of crowds at exits) which layout configuration performed best, using either method.

The evacuation time could not be calculated using the MDP method. Only the amount of epochs after which the solution is converged. A 95% threshold is added to Figure 4.2, Figure 4.3, and Figure 4.4. At the moment, the epochs cannot be thought of as a time unit, because there is no population size per state threshold defined. This means that, in essence, a large portion of pedestrians could be located in one state, which is unrealistic. Therefore no evacuation time is calculated for the MDP case. However, listing the layouts in order of evacuation time for the DFS method and in order of epochs in MDP can say something which layouts evacuate the fastest. This conclusion can be seen in Table 4.2 and both DFS $N = 50$ and $N = 100$ arrive at the same conclusion. The MDP method identifies similar best and second-best layouts, only the third and fourth performing layouts are in a different order.

	DFS (N=50)	DFS (N=100)	MDP (N=336)
1	all	all	all
2	opposite	opposite	opposite
3	one	one	adjacent
4	adjacent	adjacent	one

Table 4.2: Comparison of the evacuation time.

The percentage of crowds at exit are slightly different between MDP and DFS however the conclusion are the same. The MDP method was not able to calculate similar evacuation times as the comparison study. However, the identified best and second-best layouts, based on convergence speed, coincided with those identified by Kurdi *et al.* [14]. In conclusion, the MDP-model was able to assess a simple layout with different exit configurations on evacuation performance. Also, the model can distinguish layouts based on how quickly the simulation converges and how well population is distributed among the exits.

5
Validation study 2 : influence of passageway configuration

5.1. Goal

Four objectives are defined for the second validation study will focus on validating the MDP-model with findings from project EGO [15, 54].

1. To recreate the early stage designs used by project EGO and identify discrepancy between the models;
2. To compare identified critical areas of the MDP-model with project EGO;
3. To compare conclusions drawn from MDP-model with project EGO;
4. To conclude the MDP-model capacity to differentiate between two designs from evacuation perspective.

First, a summary is given of project EGO and which metrics the authors used to measure how well a design performed. Secondly, a sensitivity study is done to conclude which input parameters are justified for the MDP-model. Thirdly, the MDP-model results are presented. And finally, conclusions and discrepancies are elaborated upon.

5.2. Paper summary

Project EGO aims to understand the relationship between ship design and crew movement, identify KPI's to assess this relationship, link evacuation software with design software, and demonstrate the model capability. The first goal of project EGO coincides partly with the main question of the thesis, which is how a design affects egress performance, and therefore project EGO is deemed suitable to validate the MDP-model. Project EGO is performed by the fire safety engineering group in collaboration between the university of Greenwich, University College London, Directorate of Sea systems, and the United Kingdom's Ministry of defense.

The design used for the analysis is a frigate type-22 with a complement of 262. The vessels has 8 decks and a overall length of approximately 146 meter, a maximum upper deck beam of 14.75 meter, and a draft of 4.75 meter. Two different frigate designs are compared with each other, and are given in Figure 5.1. Only two of the eight decks were different between the two frigate designs. Three different resolutions were used for the comparison study, a low- ,medium- , and high-resolution layout. These different resolutions reflect different stages in ship design where different layout information is available. The low-resolution model represents an early stage layout and, for example, lacks the location of furniture in the cabins.

The paper makes use of a two different software models and evaluates different designs, for different scenarios, on a range of performance metrics. The software used is PARAMARINE – SURFCON for ship design and maritimeEXODUS for evacuation modeling. An explanation how the latter model works is given in subsection 2.4.2. In short, the model takes each evacuee individually into account, where each individual has properties that influence its behavior. The software is also capable of assigning individual agents different goals, for example, search for survivors.

Each simulation is done for different scenarios which reflect vessel operations. Seven different evaluation scenarios were defined both for normal operations (4) as emergency scenarios (3). The scenarios performance was measured using a Human Performance Metric (HPM). Only the emergency scenarios are evaluated for this study, due to the other scenarios being out of the scope of the thesis. The emergency scenarios are;

- ES1: Crew moves from normal day location to emergency station
- ES2: Crew moves from emergency station to muster station
- ES3: Crew moves from action station to muster station

For each scenario a weighted HPM was calculated. This metric is the sum of the normalized performance metric, multiplied by a weight factor. 18 performance metrics were defined which are divided in 2 congestion criteria (C1 and C2), 5 general criteria (G1 to G5), and 11 geometric criteria (M1 to M3, M5, M8, M13 to M18), and are listed in Table 5.2. All criteria greyed out are considered not calculable by the MDP-model, as of yet. Some criteria are also not viable for early ship design, since not all design characteristics are known. For example, the location of the watertight doors can still be unknown to the designer, thus the amount of times an evacuee has to open a watertight door is deemed incalculable during early stage.

Only the results of the early stage calculations are given. The medium- and detailed-layouts are out of the scope of this thesis. The results of the low-resolution model are given in Table 5.1.

	Evaluation scenario	Scenario weight	BL	VR1	% Difference between baseline and variant 1
ES_1	**Normal day cruising A**	1	38.75	43.55	-12.4%
ES_2	**Normal day cruising B**	1	46.19	45.61	1.3%
ES_3	**Action stations evacuation**	1	45.93	40.80	11.2%
	Overall performance of design		370.3	373.0	

Table 5.1: Scenario scores for emergency scenarios, copied from Casarosa [15] chapter 4 - Table 4.4.7

The NOP-scenarios are excluded from the table, the overall design performance is based on the above three scenarios. Results are given in Table 5.1 and show that the variant 1 (V1) design performed slightly better than the baseline (BL) design. ES_1 involves movement of crew from their normal day cruising locations towards the emergency stations. The baseline model outperformed variant 1 by 12.4% for C_1 but 11.2% worse for C_3. Only for the normal day cursing B do both layouts perform almost equally.

Variant 1 model outperforms the baseline model if the normal operation scenarios are also considered. This is because the variant 1 design performed better on the normal operation scenarios. Casarosa [15] was able to identify congestion locations and, by adding an additional ladder, the congestion could improved. The baseline model improved significantly after this improvement was realized. However, these improvements were only applied to the high-resolution model, and not for the low-resolution model.

[1] The metric *Time to reach final state* is assumed to the equivalent of the MDP model metric: amount of epochs until convergence

HPM performance metrics	Definition
Congestion criteria	
C1	the number of locations in which the population density exceeds 4 p/m2 for more than 10% of the overall scenario time
C2	the maximum time that the population density exceeded the regulatory maximum of 4 p/m2 for 10% of the simulation time
General criteria	
G1	average time required to complete all operations
G2	average time spent in transition
G3	time to reach final state[1]
G4	average time spent in congestion
G5	average distance travelled
Geometric criteria	
M1	the number of WTD used during the scenario
M2	the number of hatches used during the scenario
M3	the number of ladders used during the scenario
M5	the number of doors used during the scenario
M8	the number of times the FG moved between decks
M13	average number of components used per member of the FG during the scenario
M14	most times a wt door was operated
M15	most times a hatch was operated
M16	average number of doors used per person
M17	average number of wt doors per person
M18	average number of hatches used

Table 5.2: List of performance metrics used for calculating HPM. All metrics that the MDP-model is currently not capable of calculating are greyed out.

5.3. Model aspects

First, all different aspects are discussed which affect the results, for example, there was some discrepancy between input of both methods. Similarly, comparing a detailed microscopic method with a macroscopic model also decreases model resemblance. These differences are highlighted and the expected influence on results are discussed. Six design aspects will be elaborated upon and its effects on the results are discussed.

1. Layout
2. Choice in amount of actions
3. Amount of decks and exit type
4. Choice in discount factor and state rewards
5. Initial distribution
6. Designated emergency stations

The layout aspects consider problems resulting from translating a continuous design to a discretized grid. Resolution is lost in this process. The aim is to minimize the difference between the MDP layout and project EGO layout. Since the grid size impacts model resolution, the size should be reasonable. For each grid an agent can either go in 4-directions or 8-directions. maritimeEXODUS gives agents 8-directions of freedom while the MDP-model only 4, hence this contrast can have implications in conclusions drawn. maritimeEXODUS also enables agents to move between decks whereas this is not yet implemented in the MDP-model. Both models implement a nearest exit strategy.

5.3.1. Layout

Four different layouts were given by [54] which are used for this validation study. The discretization of the layout to a graph network used by the MDP method is discussed in this section. Deck number 1 for the baseline design is modelled with a grid size of approximately $1m^2$ and one with $0.6m^2$. The policy and utility distribution is plotted and shown in Figure 5.2. A discount factor of 0.95 is used and action certainty probability of 0.9. These values are kept constant for all following calculations. A high discount factor means more value is given to rewards received in the future. A high action certainty probability means evacuees follow the most optimal policies with a high probability. It is assumed that crew on a frigate will most likely traverse the optimal path to an exit.

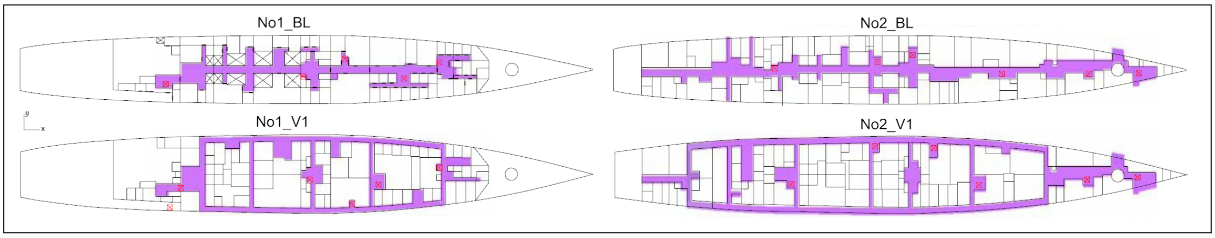
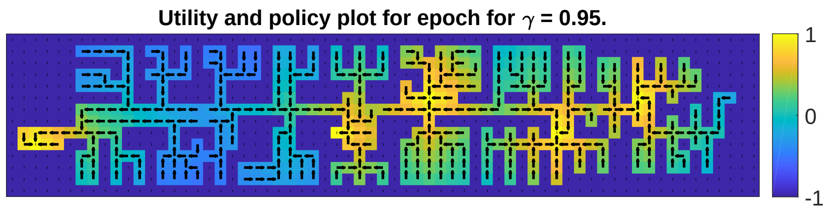
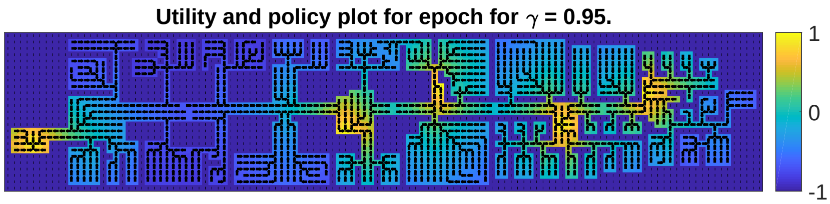


Figure 5.1: Example layout drawn in Rhinoceros with the passageway figure covered on top.



(a) Grid size of approximately $1m^2$



(b) Grid size of approximately $0.6m^2$

Figure 5.2: Policy and utility plot for no1 BL for two grids with different resolutions.

The color intensity in above figures is a function of the amount of nodes until an exit is reached, the action probability, and the discount value. The exit states have a utility of 1 and have the lightest color. Dark regions are furthest away from an exit. Adjacent grid nodes where policies result in different exits, indicate a dividing line between two areas. Each area will 'most likely' end up at a different exit. These dividing lines influence exit convergence behavior.

The exit convergence behavior for all layouts is plotted in Figure 5.3 and indicate the percentage, or probability, of the population that has reached an exit state node. Also, a 95% mark has been added indicating when the majority of the population has reached an exit. For the $1m^2$-grid this mark is reached after 24 time-steps, whereas for the $0.6m^2$-grid it reaches this mark after 40 time-steps, which is 67% slower. However, the difference is inversely proportional to the grid size. The convergence rate is, relative to the grid size, the same for the both grids.

The difference in exit $\%$ for the same exits is caused by the difference in dividing line locations. As can be seen in Figure 5.2, not all of these locations are similar. An example where the location of the dividing line can affect the exit behavior, is given in Figure 5.4. If the green line is a doorway, all agents

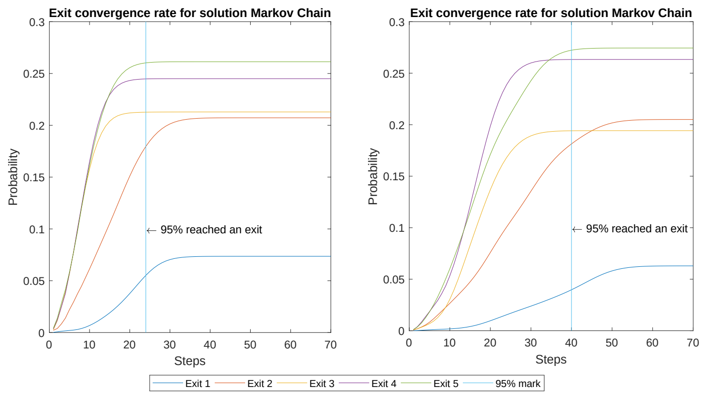


Figure 5.3: Exit convergence behavior for no1 BL for $1m^2$ (left) and $0.6m^2$ (right)

in the compartment will egress to the right. If the red line is a doorway, all agents will egress to the left. These situations are more likely to occur with lower resolution models. Therefore, some compartments end up in a different exit for $0.6m^2$ in Figure 5.2. With a higher resolution grid this sensitivity can be reduced and thus a resolution of approximately $0.6m^2$ is used for the validation study.

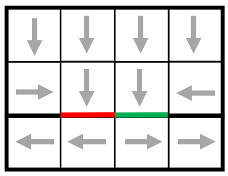


Figure 5.4: Example with an arbitrary layout where the compartment exit location choice influences results.

5.3.2. Choice of actions

The software used by project EGO for evacuation analysis is maritimeEXODUS. The agents are able to move in 8 different directions in maritimeEXODUS and 4 directions in the MDP model. This difference could cause a difference in results. It is assumed that more directional freedom does not necessarily change a persons egress behavior. Only a quicker convergence is expected since diagonal movements are more efficient, unless this is accounted for. If unaccounted for, the agent will cover 41% more distance when choosing the diagonal action compared to a non-diagonal action. This has to be compensated in the software to even out with transverse and longitudinal action directions. The added value of 8-directional freedom did not outweigh the increase in accuracy of results. The goal is to differentiate between designs and identify critical areas. It is assumed that the difference in results will remain the same whether 4 or 8 directional freedom is used.

5.3.3. Amount of decks and exit type

maritimeEXODUS is capable of linking each deck with adjacent decks. The frigate consists of 8 decks and the two different designs only vary for two decks. Casarosa [15] modelled all decks and defined for all exits the specific exit type. Each type determines the speed and amount of passengers able to transit the nodes [15]. Staircase or ladder types used by maritimeEXODUS and SURFCON are given in the list below.

- Internal and external stairs
  - Connects deck
  - Connects with outside

- Vertical ladders
  - Horizontal hatch with vertical ladder
  - Emergency exit with vertical ladder

Vertical ladders consists of 3 elements, 1 ladder transit node and 2 free space nodes. Stairs are defined by a series of nodes between the two decks. Based on the height between the decks and the step height, the software program automatically calculates the number of steps, and therefore states, for each stairway. The MDP-model has no decks connected with each other and models each deck individually. It is assumed that the emergency stations are located above deck No1 and No2. Next, when agents will move straight towards the emergency stations and thus do not leave exit nodes at deck No1 and No2. Based on this assumptions it was not deemed necessary to connect the decks. Analyzing each deck individually is assumed sufficient. However, it is noted that crew, using a certain exit on the deck below, will affect how quickly crew can escape on the deck above. Due to crowding within the staircase. No flow restrictions are incorporated in the MDP-model.

5.3.4. Choice in discount factor and state rewards

The input of the MDP-model has influence on the results and therefore on the conclusions drawn from this validation study. This section will describe why a certain discount factor and state reward is chosen. In order to do this, a utility histogram is plotted for layout No1 BL to show the influence the state rewards and discount factor have on the utility distribution. The utility distribution is used to determine all policies. Figure 5.5 indicates that higher state rewards will shift the peak to the right, increase the frequency of the peak, and lowers the standard deviation.

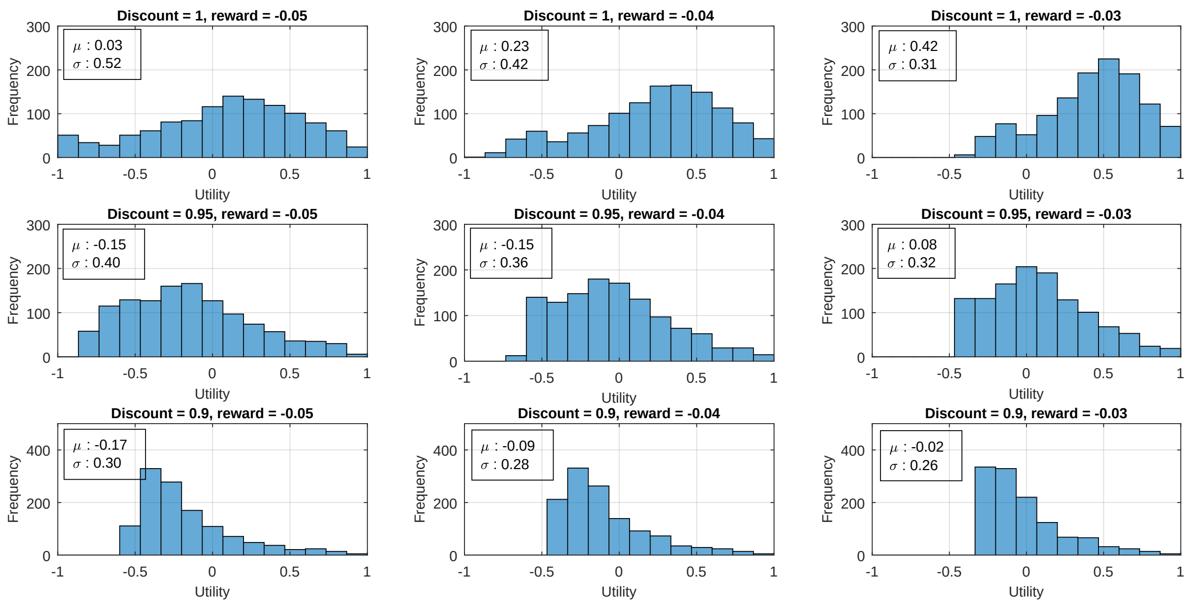


Figure 5.5: Histogram for layout no1 bl with three different discount factors (1, 0.95, and 0.9) and three different state rewards (-0.05, -0.04, and -0.03)

A discount factor of 0.95 and state rewards of -0.04 is used for further computations. The high discount factor is due to crew having knowledge of the layout of the vessel. These values result in a histogram where the layout differences are captured in variations of the histogram parameters.

5.3.5. Initial distribution

The emergency scenarios are based on the Naval Ship Code, which are rules published by the NATO as Allied Naval Engineering Publication 77. Chapter VII – Escape, Evacuation and Rescue describes the rules necessary to meet the goals of said chapter. These goals are described by regulation 0 and ensure that the design shall:

1.1 provide effective escape for all embarked persons from all manned spaces to a place of safety in the event of foreseeable accidents and emergencies at least until the threat has receded; 1.2 provide an effective means of evacuation from the ship; 1.3 provide an effective means of recovering persons from the sea.

Regulation 3 of chapter VII of the Naval Ship Code stipulates the evacuation analysis and demonstration rules. Alternative to these rules, the naval administration may accept the use regulation from a validated classification society, international conventions, or a suitable validated alternative approach. The international convention approach is described in section 2.1, the alternative approach described in subsection 2.1.2.

The analysis described in the Naval Ship Code is similar to the analysis described by IMO in Circ.1533, only with few exceptions. These exceptions are described in VII – regulation 3 – paragraph § 8. The exceptions are regarding the evacuation target times, range of watertight integrity conditions, and a minimum of 6 scenarios is to be considered. The initial distribution of persons should be representative for the vessel's operations. The initial distribution of crew is not given by the validation study and whether a distribution based on different operations is used, or based on the FSS, is unknown. However, it is stated that the scenarios do not accurately model actual naval operations. Therefore, a distributed crew in compliance with FSS code is used and is assumed to be sufficiently representable.

Since no compartment information is given, and therefore the function of each compartment is unknown, a *best guess* is made based on location and size. The assumed function for each compartment for each deck is given in Figure 5.6. The compartment type will be used to create an initial distribution. Table 3.1 is used for ratio of crew for each space type.

A minimum of four scenarios should be considered regarding the distribution of persons on board, as stipulated by Circ.1533 [24], see subsection 2.1.1. Since it is unclear whether the vertical zones are defined in early stage, only two cases are simulated. For the night case (case 1) 2/3th of the crew is located in accommodation spaces and 1/3th of the crew is located in the service spaces. For the day case (case 2) 1/3th the crew is evenly distributed among the public spaces, the accommodation spaces, and the service spaces. The initial distribution table with the assumed compartment types and amount of states belonging to each type is given in Table 5.3. The percentage of a certain compartment type compared to total states is given in Table 5.4. The final layout used with all compartment allocated to a specific type is graphically plotted in Figure 5.6.

Compartment type	Layout			
	No1 BL	No1 V1	No2 BL	No2 V1
Wall	1674	1532	2640	2416
Corridors	423	628	587	884
Exits	5	5	6	6
Service spaces	334	299	823	790
Public spaces	323	303	281	257
Accomodation	130	122	118	102

Table 5.3: Number states for each layout type

Compartment type	Compartment type states / total states			
	No1 BL	No1 V1	No2 BL	No2 V2
Service space	42%	42%	67%	69%
Public space	41%	41%	23%	22%
Accomodation	17%	17%	10%	9%

Table 5.4: Ratio of compartment type with total amount of states

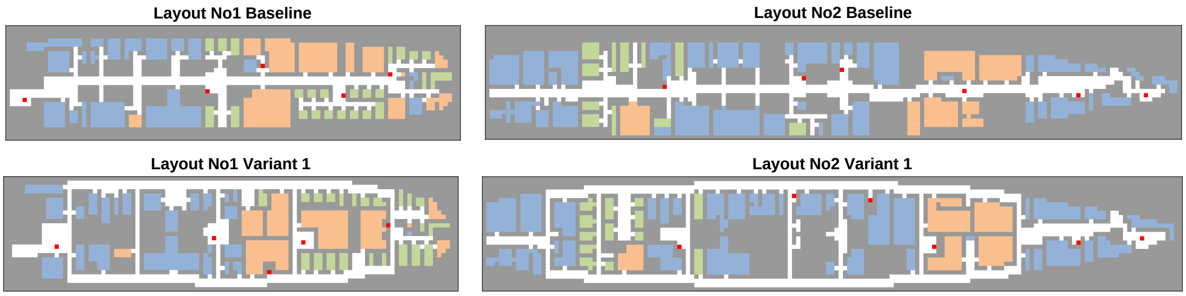


Figure 5.6: Assumed compartment type. Blue denote service spaces, orange denote public spaces, and green denote accommodation spaces.

5.3.6. Designated emergency stations

The emergency scenarios each have their own initial distribution and final destinations for each crew member. However, this information is not given. An assumptions is made that each crew member moves in an *upward* direction towards the deck above him. Emergency stations should be located near embarkation stations [63], which are assumed to be located above the decks given in Figure 5.1.

5.4. MDP results

Previous section described the influences of the model aspects on the outcome and conclusions. The conclusion from previous section will serve to justify input for the MDP-model for the validation study. The action certainty is 0.9, the discount factor is 0.95, the state rewards -0.04, and the exit reward 1. This reflects a crew following optimal evacuation policies with high accuracy and valuing future safety over immediate safety. No hazards are modelled and therefore all states have the same negative reward. The layout used is given in Figure 5.7 below. The compartment types are given in Figure 5.6.

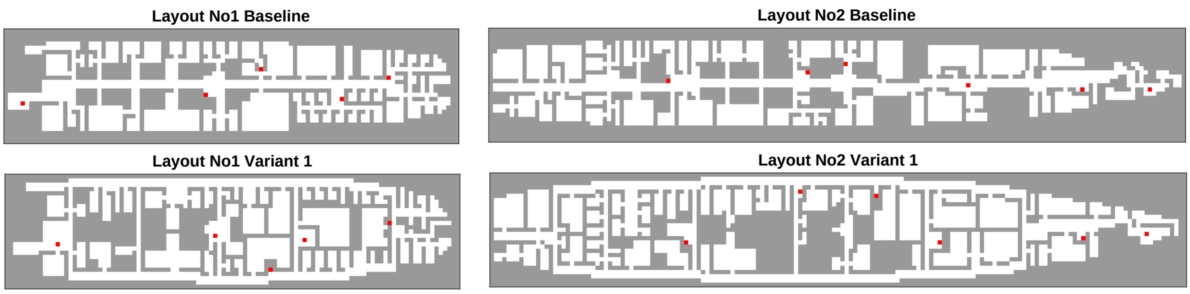


Figure 5.7: Project EGO layouts translated in MDP program, gray indicates walls, white are states, red is an exit state. Exits are number from aft to forward in ascending order.

The amount of epochs used for solving the Bellman equation, see Equation 3.6, is 100. This value ensures all states in the layout are reached by the value iteration algorithm. This also ensures that if a random state is chosen, and the policies are follow, an exit is found. If less epochs are chosen then states which are a distance equal to amount of epochs away from exits are not reachable or agents do not have enough time to move towards an exit. This is shown in Figure 5.8 below.

It also becomes apparent which region is furthest away from the exits, or is most isolated. An animation plot of the value iteration gives insight which areas are difficult to reach, after how many epochs each state is reached, and after how many epochs the solutions remains the same. The solution tends to not change much after all states are reached, some policies keep alternating between two actions however these will not change the final solution. The isolated regions in combination with the initial distribution influence the convergence behavior for all the exits.

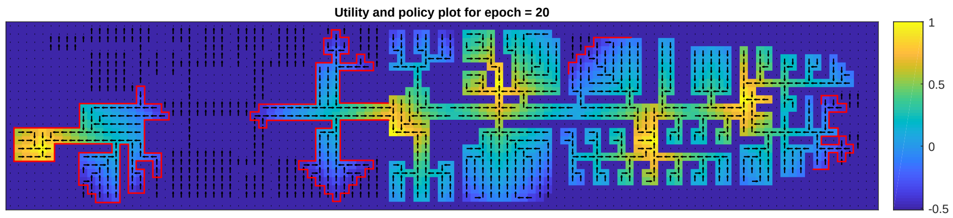
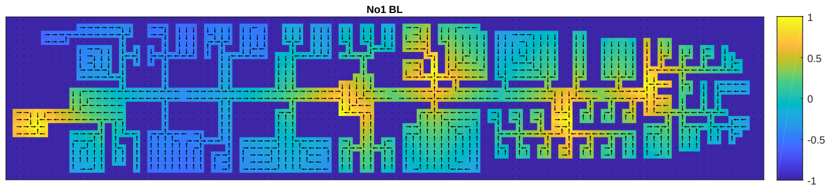
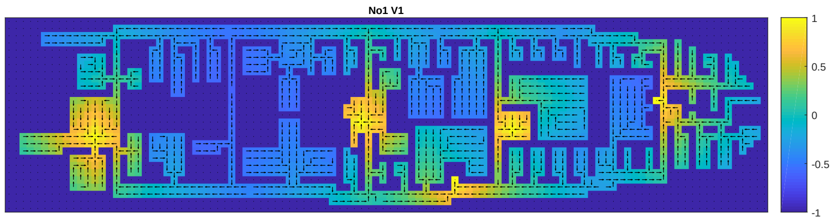


Figure 5.8: Snapshot of the value iteration algorithm for layout No1 baseline after 20 iterations showing the area which has found a solution and which area has not. Red indicates the dividing line between the two areas.

The final utility and policy plot for all decks are given in Figure 5.9 and Figure 5.10. All exit states are bright yellow and the states furthest away dark blue. Therefore dark regions indicate remote areas of the layout and occupants located there take longest to reach an exit. From these figure it can also be seen which compartments egress to which exits by following the policies.

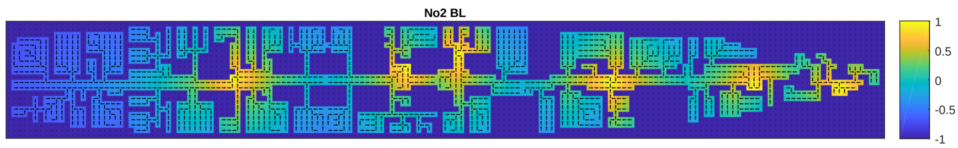


(a) Utility and policy plot for No1 BL

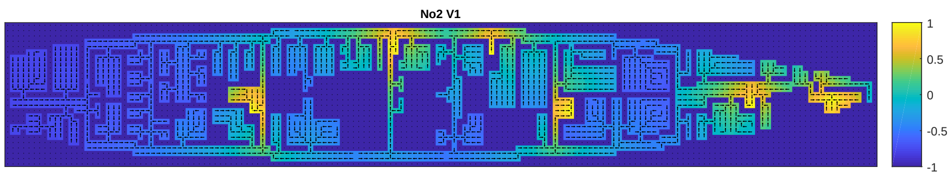


(b) Utility and policy plot for No1 V1

Figure 5.9: Policy and utility plot for no1 BL for two grids with different resolution



(a) Utility and policy plot for No2 BL



(b) Utility and policy plot for No2 V1

Figure 5.10: Policy and utility plot for no1 BL for two grids with different resolution

5.4.1. Exit convergence results

The exit convergence behavior for case 1 (day) and case 2 (night) have been plotted in Figure 5.11 and Figure 5.12. The final convergence values for both figures are given in Appendix A, Table A.1 and Table A.2. A 95% mark has been added to indicate after how many epochs the majority of evacuees have reached an exit. This mark is also used as a performance metric to compare the designs. Both design variants show similar convergence results for deck No1 night case . Exit behavior for exit 1 and 2 is also in accordance with Figure 5.8 where it can be seen that crew located furthest away egress to these exits. Therefore, these exits converge slowest. First, a comparison between layouts for each deck is given, after that a comparison between the day and night cases is give.

Deck No1 outperformed deck No2 for both layouts as well as the cases. This is due to deck No1 being smaller in size and better placed exits and therefore evacuees have to, on average, traverse less distance towards exits. There is a difference of 20% (or 7 moves) between the baseline decks, and 63% (or 26 moves) between the variant 1 decks. In addition, the population evacuating deck No1 is distributed more evenly amongst the exits, indicating that the exits of deck No1 is better distributed than deck No2, regardless of passageway configuration. Whether this difference in population distribution amongst the exits is beneficial depends on the staircase capacity. The exit usage should relate to the staircase capacity, however, for this study the exits capacity, or staircase capacity, is assumed to be unknown.

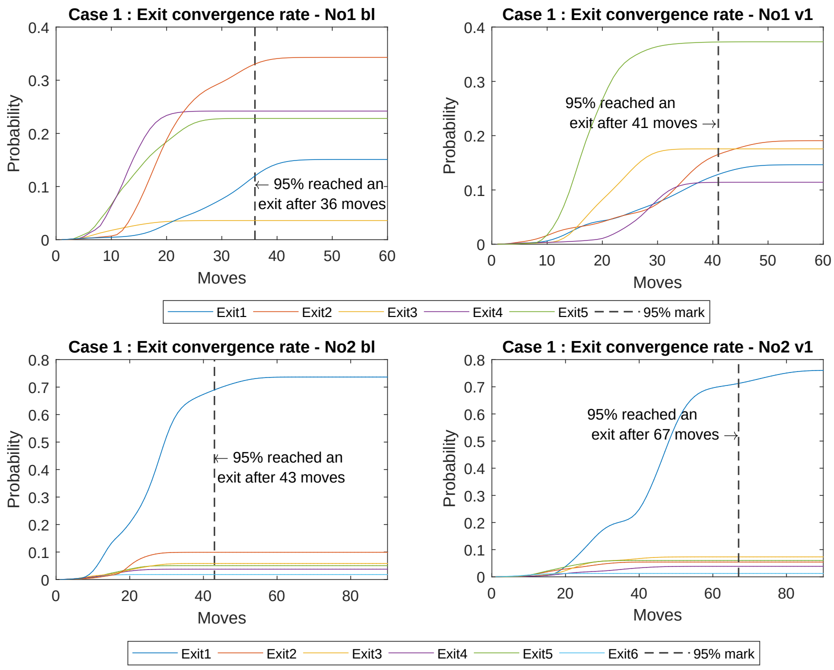


Figure 5.11: Exit percentage with distribution based on FSS - case 1

The bottleneck exits, or slowest converging exits, for case 1 are exits 1 and 2. For case 2 exit 1 is converging the slowest for all layouts. This indicates that isolated areas are near exits 1 and 2, which is at the aft of the vessel. The wavy exit 1 curve at deck No2 for the variant 1 layout is caused by different regions of the layout reaching an exit at different intervals. Each compartment has its own cumulative probability and the larger the room the larger the impact all evacuees have on exit convergence behavior when they reach an exit. The steepness is determined by the rate of crew reaching an exit. A more steep curve indicates a higher amount of population percentage per epoch that arrive at an exit. A steep curve could indicate possible congestion at that exit. In reality the steepness is limited, since there exists a maximum amount of persons per time unit that can enter an exit.

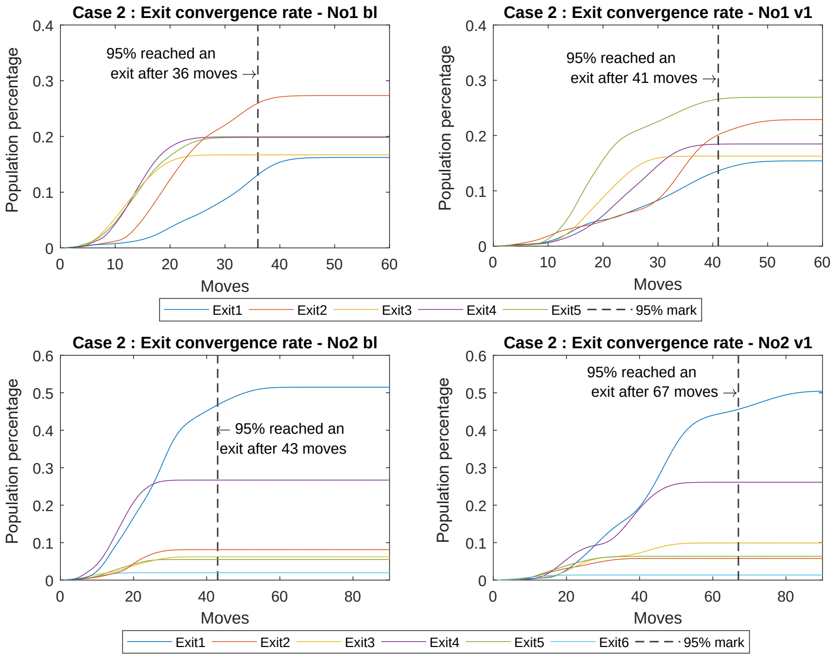


Figure 5.12: Exit percentage with distribution based on FSS - case 2

The least used exits coincide with the isolated exits from the initial distribution point of view. The population is most dispersed during the day case, where 1/3th of the crew is located in each space type. This results in a more evenly distributed population among the exits, as can be seen from the results. A comparison between the standard deviations of the final exit distribution is given in Appendix A Table A.3. The same approach as Casarosa [15] has been used to normalize the results and sum them to get an overall score. However, due to the limited amount of performance metrics it is uncertain how usable this metric is. If layout configurations are compared on exit distribution, then the variant 1 layout outperforms the baseline model for case 1 deck No1, and case 2 deck No2. The baseline layout outperforms variant 1 regarding convergence speed for deck No1 (5 epoch difference) and significantly outperforms for deck No2 (24 epoch difference). There is no difference in convergence speed between day and night cases. There is a difference between exit usage which is expected since population is distributed differently.

	95% mark reached after # moves	
Layout	case 1	case 2
No1 BL	36	36
No1 V1	41	41
No2 BL	43	43
No2 V1	67	67

Table 5.5: Amount of moves per layout per case

5.4.2. Utility histogram

The utilities distribution for 100 epochs for each layout have been plotted in a histogram in Figure 5.13. These distribution indicate how close each state is to an exit, and therefore it can assess the layout. The choice in state reward and discount factor have a tremendous influence on these results, as has been discussed in subsection 5.3.4. These variables are kept constant for each deck which gives the possibility to compare each layout with each other.

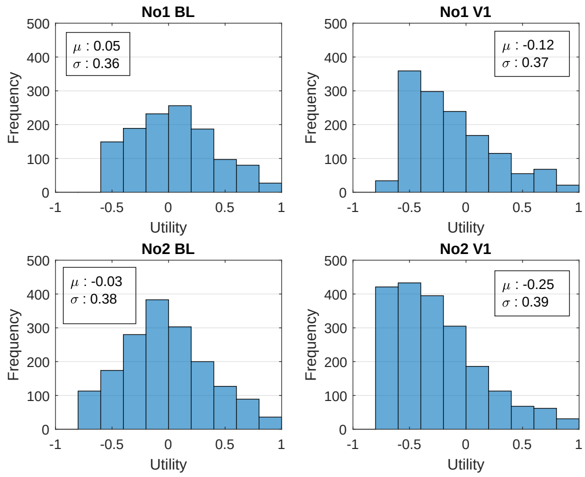


Figure 5.13: Utility frequency plot

A high mean utility value indicates all states are relatively close to an exit. Therefore a high mean represents a layout where exits are more evenly located. The baseline layouts have the highest mean compared to the variant 1 layout. The upper decks have both also a higher mean compared to the lower decks. Which is probable since the lower decks (No 2) have a higher amount of states per exit than the upper decks. The average amount of states per exit values are 242 for No1 BL, 270 for No1 V1, 301 for No2 BL, and 338 for No2 V1.

The standard deviation indicates how many state utilities deviate from the mean. A high standard deviation indicates many states deviate from the mean, a low deviation means the opposite. A low standard deviation coincides with a larger amount of isolated compartments than a high standard distribution. The latter indicate large amount of evenly distributed compartments given that the discount factor and state rewards are equal for both comparison designs, see Figure 3.4. From this perspective a high mean is preferred over a low mean, therefore the baseline performs better than the variant 1. A high standard deviation is preferred over a low standard deviation if the mean is low. If the mean is high than a low standard deviation is preferred indicating that a lot of compartments are located close to an exit. The difference of the standard deviations between the baseline and variant 1 model is small.

5.4.3. Maximum probability occurring during simulation

The MDP-model uses a transition matrix and initial state distribution matrix to simulate the evacuation of crew. Each iteration involves multiplying the previous state vector with the transition matrix to get the new distribution. If the state vectors for each iteration are concatenated to create an additional solution matrix, then for each state the maximal occurring probability can be found. This value indicates that at some point during the simulation, a certain amount of crew occupied that state. Congestion could be identified using this value as a metric, which is a function of crew and state geometric properties.

Congestion is defined as a certain amount of persons per square meter [16]. For the SOLAS simplified approach the criteria is 3.5 persons per m^2, whereas for the advanced approach it is 4 persons per m^2. Casarosa [15] used 4 persons per m^2, since the approach utilized by maritimeEXODUS is an advanced approach. The following figures uses a congestion criteria of 3.5 persons per m^2 since the MDP-model is an early stage simplified model (agents are not modelled individually).

The frigate has a complement of 262 crew members but the distribution has not been given. An indication of the distribution is given with table D-2 and D-3 from Casarosa [15]. These tables give results of the blanket search scenario for the low resolution model. Counting crew for each deck results in 30 crew members for deck no1 and 70 crew members for deck no2. Resulting congestion threshold values are given in Table 5.6.

Deck	Crew		Congestion threshold	
	Total [-]	Single [%]	[pers/m2]	[% / state]
No1	30	3.33	3.5	7
No2	70	1.42	3.5	3

Table 5.6: Congestion threshold parameters

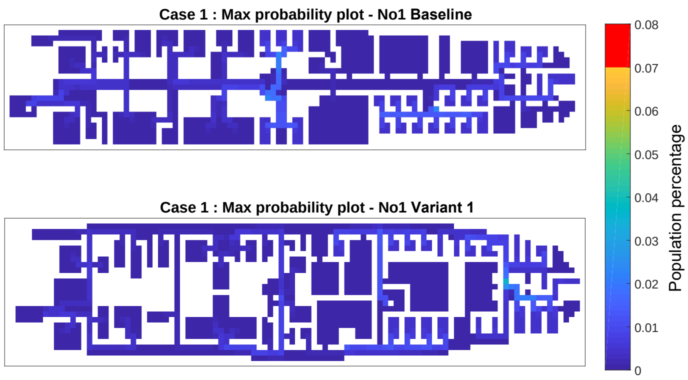


Figure 5.14: Maximum probability occurring for each state is plotted per layout, the congestion threshold is 0.07%.

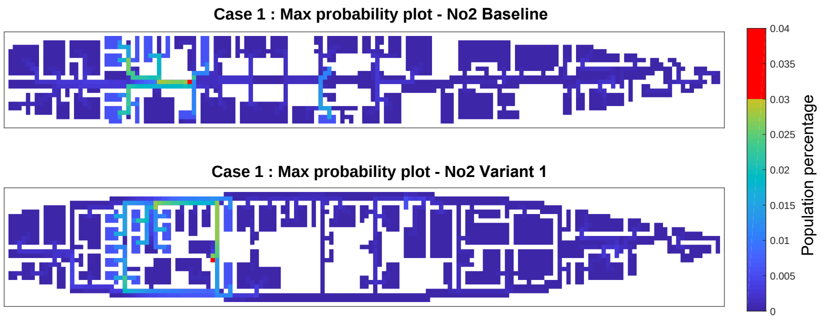


Figure 5.15: Maximum probability occurring for each state is plotted per layout, the congestion threshold is 0.07%.

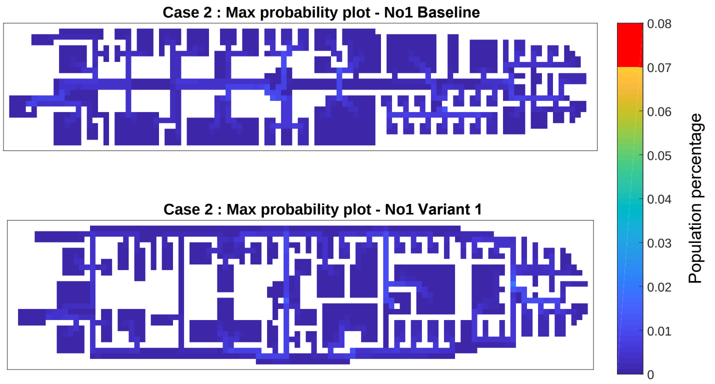


Figure 5.16: Maximum probability occurring for each state is plotted in a single layout. The congestion threshold is 0.03%

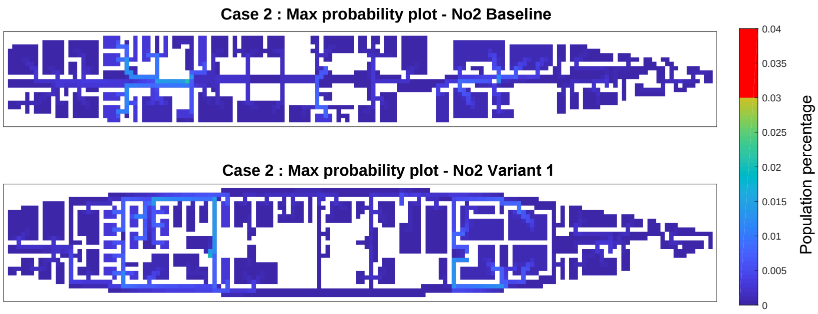


Figure 5.17: Maximum probability occurring for each state is plotted per layout, the congestion threshold is 0.07%

5.5. Additional damage case

It is probable that a damage occurred causing the initialization of an evacuation. Only considering evacuation cases without any damage that affects personnel movement seems insufficient. A better understanding of the evacuation performance can be gained by evaluating ship designs and considering multiple, probable, scenarios. Casarosa [15] defined both evacuation scenarios as well as normal operation scenarios to create an outline of different situations that may occur during the operational life of the ship. However, no damage scenarios were considered to the author of this thesis knowledge. A damage that disables a stairwell or blocks a passageway could occur during an evacuation. The result is that the certain flight options are eliminated and evacuees have to take alternative escape routes. These variations to the normal evacuation also affects the evacuation performance of the two designs. The assessment of scenario deviations helps better understand design adaptability, or escape arrangement flexibility. Analyzing escape arrangement flexibility is one of the objectives of performing an evacuation analysis as described by IMO guidelines [24]. These variations should also be taken into account to better judge each design on its egress performance.

Thus an additional damage case has been defined to demonstrate the escape arrangement flexibility of both designs. Which in turn reduces uncertainty in conclusions drawn on evacuation performance of both layouts, ergo which performs best. Only deck No2 will be investigated in more detail, since this deck seems to be most critical. Various damage cases could be considered. Examples are, blocking a part of the passageway which could be caused by a fire, or by removing an exit from the layout to simulate a case where one staircase is obstructed. The design redundancy and adaptability can be outlined by performing a range of damage cases. Each of these scenarios can help gain insight in how and where a design can be further improved. However, this is not the goal of this section. This section will demonstrate the MDP-model capability to assess a damage case.

The damage case to further assess layout redundancy will be a case where the most critical exit is blocked or obstructed from use. The worst performing deck is deck No2, where exit 1 was deemed most critical. Results of the damage case are given in Table 5.7 and plotted Figure 5.18. The maximum occurring probabilities are given in the appendix, see section A.2. Congestion only occurred for the baseline model. Two areas can be identified for the night case where population percentage exceeded 3% per state, the states are colored red where this exceedance occurs. Throughout the variant 1 layout the population percentage remained below the threshold. Hence, the variant 1 layout outperformed the baseline model regarding possible congestion. This can be a result of the availability of multiple routes towards an exit for the parallel passageway configuration.

Metrics		**Baseline** Case 1	**Baseline** Case 2	**Variant 1** Case 1	**Variant 1** Case 2
$\mu_{utility}$		-0.21		-0.35	
$\sigma_{utility}$		0.47		0.41	
95% mark		82		92	
Percentage of population at exit	2	0.847	0.596	0.807	0.544
	3	0.062	0.062	0.074	0.099
	4	0.016	0.267	0.023	0.261
	5	0.055	0.055	0.064	0.064
	6	0.020	0.197	0.014	0.014

Table 5.7: Summary of results for the damage case

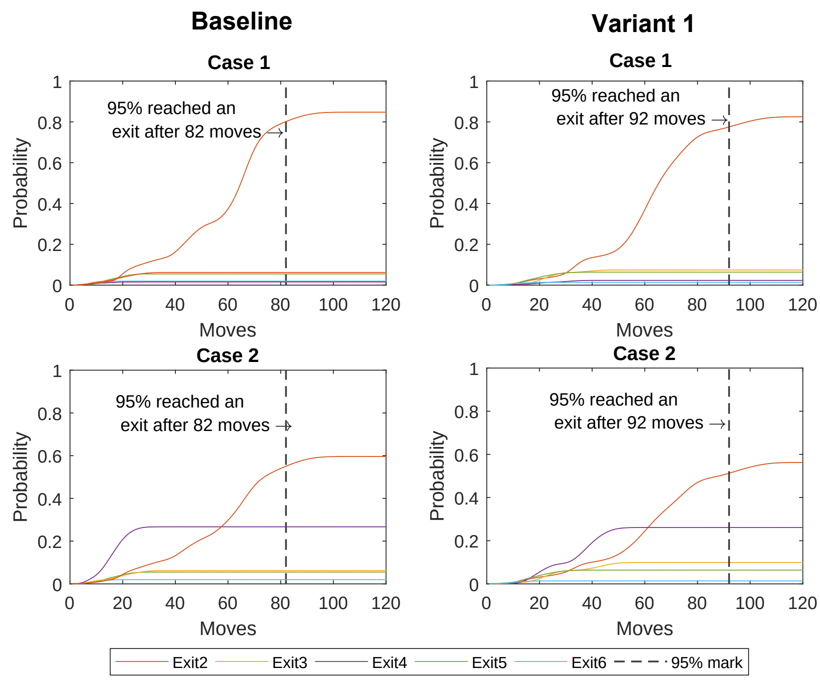


Figure 5.18: Exit percentage results when exit 1 is removed for deck No2.

Results show that the baseline layout, having a single passageway throughout the ship, still outperforms the variant 1 layout. The population distribution among the exits are almost equal for both layouts. The majority of the crew has evacuated after 82 epochs for the baseline layout, and after 92 epochs for the variant 1 layout. This is an increase of $82 - 43 = 39$ epochs for the baseline layout, and $92 - 67 = 25$ epochs for the variant 1 model. Indicating that the variant 1 model evacuation time only increases by 27% whereas the baseline layout increase by 90%. There is no difference between speed of convergence between day and night case.

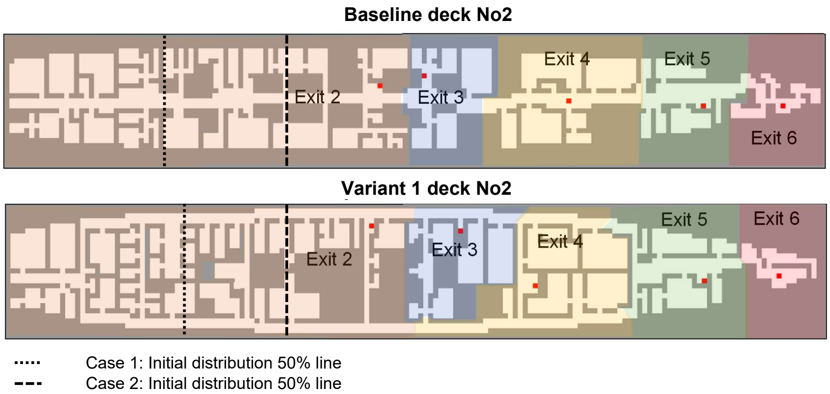


Figure 5.19: Layout areas that indicate which part of the population will evacuate to the nearest exit. Two lines are added indicating the dividing line, 50% of the population is located left of this line.

Figure 5.19 shows the layout areas where population will egress towards a certain exit. The exit the crew will move to, according the MDP model, are the red states in each area. Two boundary lines are plotted for both layouts which split the population in half. This is done for both cases to indicate that more than half of the population is located aft of exit 2. Which results in exit 2 being the most used exit.

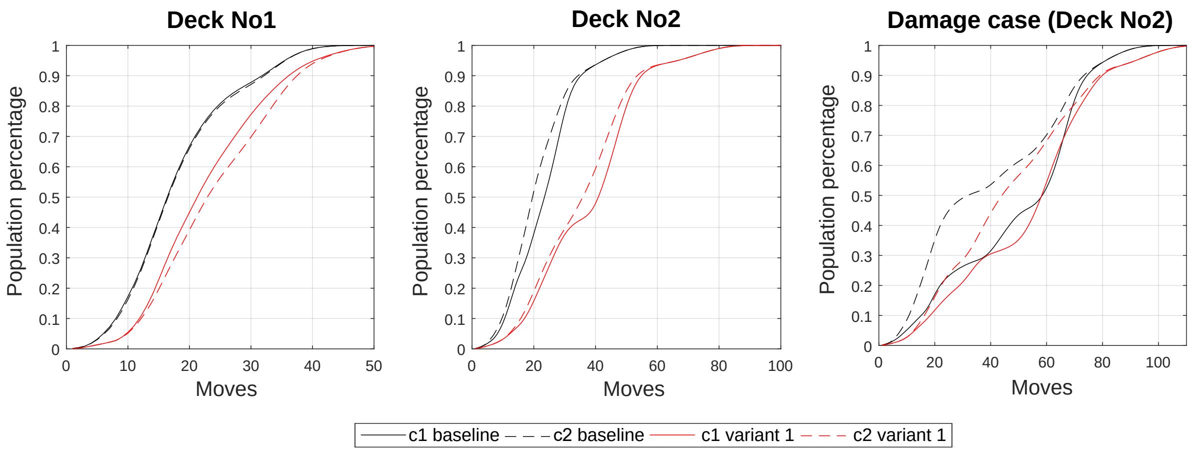


Figure 5.20: Comparison of percentage of population reaching an exit state for both decks and additional damage case.

Lastly, Figure 5.20 shows for both decks, and the additional damage case, the total percentage of the population that has reached and exit, per epoch. No difference in convergence speed was noticed between day and night cases. However, Figure 5.20 does show different evacuation behavior between the day and night cases, which is expected since there is a difference in initial population distribution. Sudden changes in the graph indicate that a large group of the population has reached an exit. The parallel passageway configuration has a property that has not been further investigated yet. The crew can always reach all the locations in the vessel when a damage, that blocks the passageway, occurs in the parallel passageway part of the vessel. This is not the case for the single passageway design, crew will then have use a different to go around the blockage. This design feature should be considered when evaluating which design performs best.

5.6. Conclusion and Discrepancy

The intention of performing an early stage ship design evacuation analysis is to gain better insight in design performance [15]. The International Maritime Organization identifies several objectives of an early stage evacuation analysis [24]. Which, if successfully conducted, improves ship safety and evacuation performance. The goal of this validation study was to recreate an early stage ship design used by Casarosa [15] and compare conclusions drawn from both models. The software program used by Casarosa [15] is maritimeEXODUS, which was able to identify critical areas and which design performed better according to a predefined human performance metric. First, the discrepancy between the models is commented upon. This discrepancy helps investigate model fidelity and understand to what extend conclusions are in agreement with each other. In addition, the model input and output variations are used to assess the level of uncertainty, or the confidence, in the final conclusion.

It should be acknowledged that the comparison made is between a simplified method[2] and an advanced method. Where a simplified and advanced method refers to the IMO definition [24]. The main difference between these methods is how the population is simulated, which is either as a whole, or each evacuee individually. The choice in approach cases a difference in method outputs, which are used to assess the design. Casarosa [15] was able to create, for both configurations, 3 different resolution layouts with each 7 different evacuation scenarios, and calculate 18 different performance metrics for each resolution layout and each scenarios. The MDP model was not able to recreate the various layouts, scenarios, and could not calculate the 18 performance metrics. These limitations are a result of employing a *simplified* method. Only a small amount of metrics, similar to those used by Casarosa [15], were able to be calculated by the MDP model.

Next, not all input information could be acquired due to the confidential nature of naval warship design. The main information lacking were the compartment types, the exact amount of crew per deck, and the initial distribution. Nonetheless, based on available information, it is assumed that MDP model input used coincides with authors input to a certain degree, and that the conclusion is still reasonably valid. Similarly, the congestion threshold applied is not yet verified, thus it is unknown if the definition used is well-grounded. Consequently, the layout performance conclusion will mainly be a based on the utility distribution, the exit behavior, and the maximum occurring probabilities. These performance metrics will be used to assess the evacuation scenario towards the emergency areas, these are assumed to be located above deck No1. This assumption results in only comparing the MDP model with evacuation scenario 1. Lastly, there was no exit flow limit defined for the MDP model, in other words, no limit was set to the amount of population able to enter an exit per epoch. A possible implementation to incorporate this would be to stretch all curves accordingly or by implementing a dynamically changing Markov chain based on state capacity. The latter idea is further explained in chapter 8. The most used exit is located aft and hence this area of the design is more critical.

From discrepancy described it can be concluded that there is still uncertainty between model likeness, and hence this should be taken into account in ascertain conclusion confidence. On the basis thereof it is concluded that the MDP model was able to differentiate between the two layouts and identify which performed best. The single passageway performed overall better than the parallel passageway. This was thought to be mainly due to crew having to traverse less distance towards exits. Next, the utility distribution determined that exits of the baseline layout were more effectively placed throughout the layout. This resulted in the baseline layout states being on average more close to an exit than the variant 1 layout states. The average distance towards the nearest exit has the most influence on the utility distribution.

No congestion was identified using the defined congestion threshold. The most probable location for congestion could be identified, which was during the night for deck No2. This was due to the clustering of accommodation spaces. At night, two-thirds of the crew is located in the accommodation spaces and could only egress towards exit 1 for deck No2. This resulted in exit 1 being most critical for deck No2. This coincides with the conclusion drawn from Casarosa [15]. If escape scenario 1 coincides with

[2] The MDP model does not share the same underlying mathematical framework as the method described by IMO guidelines [24], but model assumptions do coincide, to a greater extend, to the simplified method assumptions.

the assumptions of the MDP-model, then conclusions of both studies are in agreement. Both studies conclude that the baseline model outperforms the variant 1 model.

Casarosa [15] concluded that in order to improve the baseline layout an additional ladder is to be added at deck No1 between exit 1 and 2, see Figure 5.1. From Figure 5.8 it can be concluded that the area between exit 1 and exit 2 is most isolated. Also this coincides with Figure 5.14 for deck No1 showing possible congestion at exit 1 and exit 2. As Casarosa [15] stated, the intention behind performing an evacuation analysis for an early stage ship design is to gain better insight in design performance. Not so much at getting precise measurements close to reality. It is concluded that the MDP model:

- Can estimate evacuation duration to a reasonable degree
- Can identify critical exits
- Show potential in analyzing escape arrangement flexibility
- Can identify areas of possible congestion

The MDP model concluded that a single passageway outperforms a parallel passageway, however a parallel passageway shows more adaptability to damage cases.

6 Discussion

The objective of this thesis is to investigate the potential of using a Markov-Decision-Process (MDP) framework to assess an early stage ship design from an evacuation perspective. One main question and four sub questions are defined. This chapter discusses the findings and its significance, this is summarized per sub-question. In addition are the method limitations discussed. The main question of this thesis is:

> *How does a ship design alter when it is egress based driven and could a Ship-Centric Markov Decision Process provide a tool for such a method in the preliminary design stage?*

The first sub-question is defined to understand for which type of vessels an evacuation analysis needs to be performed and how other industries perform such an analysis. The second sub-question focuses on the functionality of similar tools and provides a basis for the method development. The relationship between design and evacuation is investigated with sub question three. Two validation studies were performed to answer this question. Finally, sub-question four will help determine to what extend the main question can be answered. The first sub-question is:

> *1. For which types of vessels does egress influence the design and how do other industries simulate egress?*

Regulation stipulates that an evacuation analysis is to be performed on ro-ro passenger ships which have a keel-laid date on or after the 1st of July 1999. New IMO amendments makes it in addition also mandatory for other passenger ships which, with a keel-laid date on or after 1 January 2020, to perform this analysis. Special purpose vessels with more than 240 personnel are also considered other passenger ships, and hence need to comply with the same guidelines. For these ship types such an analysis assesses the evacuation performance and their findings can affect the design. The regulation guidelines give benchmark data to compare results with. This data originates from the building industry. The building industry models egress with similar software methods, utilizing both macroscopic as microscopic approaches. In addition, different specific egress strategies are defined for different emergencies. The evacuation process defined in the offshore industry shares a similar structure as the marine industry process. In addition, challenges imposed by the environment are also similar. The offshore industry focus on risk-based methods to improve the evacuation, escape and rescue (EER) process.

> *2. What information is necessary for an egress model as input and what information should the model provide the designer.*

The capabilities of an evacuation model depend on the applied underlying principle, which can be based on an optimization methodology, on a simulation approach, or on a risk-based-assessment [59]. Either principle needs information regarding population, enclosure, and behavior as input. Model input information is partly determined by whether or not the population is treated as individuals or as a group. Regulation stipulates which specific information is necessary for the different approaches [3, 24]. The choice in population definition also affects how behavior is considered. The simplified method, considering the population as a whole, is more appropriate to use for an early stage ship design due to the ease in ability to provide an approximation of the vessels evacuation performance [24]. The behavior of a single evacuee cannot be simulated when agents are not modelled individually. This contributes to a reduced model fidelity and hence result accuracy is lost. Population characteristics are mainly a function of ship type, which affects the population demographics, awareness, and response times. The model output depends on the application of the egress tool. The evacuation time is the most important output variable when the model is used to check if design meets the IMO criteria. The goal should be, to be able to confirm that the design meet required criteria, identify and eliminate congestion, demonstrate escape arrangement flexibility, identify areas of counter- and cross flow, and provide evacuation information to the operators [24]. Model output should facilitate information to asses either some or all of these goals.

3. *How does general arrangement design influence egress?*

The general arrangement is a function of various factors, such as the ship type and ship requirements. Passenger vessels include many public areas whereas special purpose vessels have in addition to crew accommodation a wide variety of service spaces. This configuration affects initial population distribution [23] in turn affecting the evacuation performance. Only two design aspects were investigated in more detail, the choice in exit locations, and the influence of the passageway configuration on an evacuation. Kurdi *et al.* [14] demonstrated the influence different exit configurations have on the evacuation duration and distribution of the population among the exits. The authors demonstrated most evenly distributed exits throughout the layout was found most beneficial to the evacuation process. Casarosa [15] demonstrated the influence of two different passageway configurations on personnel movement on board a frigate. The conclusions were based on a human performance metric (HPM) to assess different scenarios and layout resolutions. The low-resolution layouts corresponded with an early stage ship design. A single passageway throughout the vessels performed overall better than two parallel passageways. This is because the population for the single passageway configuration had to, on average, traverse less distance towards an exit. Similarly, the exits were more evenly placed throughout the layout. The additional damage case showed that the parallel passageway configuration performance was less sensitive when the most critical exit was removed. This could lead to the conclusion that a parallel passageway is more redundant and escape arrangement more flexible. This design was further improved by eliminating congestion through adding an additional ladder. Both studies showed the major influence exit placement has on egress performance.

4. *Is an SC-MDP a viable method for modeling egress in general and which aspects of egress is it able to capture?*

From the literature study it is concluded that the amount of vessels which have to perform an evacuation analysis will increase. The new amendments could create an increase in the demand for evacuation models or evacuation research. The diversity in the various models are due to the complexity of an evacuation process. Different models are able to capture different aspects of the highly dynamic system. A Markov-Decision-Process is probabilistic approach to simulate system behavior. The validation studies determined that the method is able to differentiate between designs and identify critical aspects, such as unevenly used exits. The second sub question describes the different elements in evacuation models and the objective of an evacuation analysis. The MDP method was not able to evaluate all of the IMO given objectives, given by [24]. This is caused by to the method assumptions. To improve the models shortcomings, improvements are suggested and given in chapter 8. The method is able to incorporate population distributions, identify critical exits, and locate possible congested areas at the time of writing. The third sub-questions demonstrated the MDP model capability to assess layouts based on on exit- and passageway configurations to a certain extend. By adding additional scenarios conclusion confidence is improved. The MDP framework demonstrated potential to simulate egress.

Regarding the limitations of this thesis and differences with other models. A noticeable difference between a Markov-Decision-Process based model and the models incorporated by the validation studies is the method approach. The MDP model is a stochastic method whereas the validation studies a deterministic method. As a result, both validation studies needed to simulated the process a hundred times to get an averaged result. Whilst the MDP-model only has to simulate the process once. This gives the advantage that the method can be faster performed and more easily used during early stage ship design. However, as also was shown in section 5.3, the methodology proposed was not able to incorporate all aspects of an evacuation, nor calculate similar metrics as Casarosa [15]. Table 5.2 shows how much criteria the MDP-model was not able to be calculate. This is a result of, as explained by sub-question 2, a choice in modeling the population as a whole. Not modeling all persons as individuals makes it unable to calculate metrics related to individuals, for example how often a watertight door is used. Improvements to the MDP-model is explained in chapter 8.

The first part of the main question - *How does a ship design alter when it is egress based drive* - is answered to a certain extend using literature on ship design, using sub-question 4, and with the two validation studies. First, the implications the ship design process has on the evacuation analysis is discussed. Then, the main question is answered using the conclusions from the two validation studies.

The capacity to modify to the layout decreases as the ship design process progresses [2]. The ship design process can be split up in three major stages [48]. This thesis focused on the first stage, the early stage, which holds the most design freedom. The concept stage follows after the early stage, and lastly detail design commences. The early design process can differ for each ship type and level of novelty of the ships design [49]. At the time of writing, an evacuation analysis tends not be performed early on in the design process [64]. The insufficient literature found on the intricate relationship between a ships design and the evacuation performance limits the ability to completely answer the first part of the main question.

The relevant decisions that occur during each stage of the design process affect how how a ships layout changes. Design modifications which improve evacuation can be justified with evacuation tools, except these tools are limited to different design stage. Model fidelity increases as models get more advanced. Simplified methods are used early in the design stage and have lower fidelity, which prevents calculating accurate evacuation times. It is unclear whether evacauability is currently incorporated in early design and used as a measure, or style. Early stage models could be used when design evolves, to frequently evaluate evacuation performance. An evacuation analysis is not always carried out during early stage ship design [64].

The general arrangement of passenger ships (both cruise ships as ferries) tend to start by determining the location of public spaces and accommodation spaces [52]. An ship arrangement will improve depending to the evacubility aspects the model is able to capture. The first validation study demonstrated that placing exits on all sides of a room improves egress performance. From the second validation study it becomes apparent that clustered accommodation compartments cause the nearest exit to be most critical. Choosing a compartment configuration which disperses the population more evenly among the layout, for both day and night cases, will reduce possible congestion inception. Staircase locations should prevent area isolated areas, but still be in agreement with the assumed population distribution. Next, it was determined that decreasing the distances towards the exits improves evacuation. Providing multiple escape options increases the evacuation redundancy of a design. However, it should be noted that above conclusions were based on limited scenarios and metrics. Increasing the scenarios considered, and including damage cases, could improve conclusion confidence. In short, a ship design will change based on the method employed and the methods capabilities. The designer can only assess as much as the tools able him or her to.

7
Conclusion

This research showed the possible demand for a model capable of evaluating evacuation performance and identifying critical areas early on in the design stage. This work successfully extended the work by Kana and Singer [12], Kana and Droste [27], who proposed a Markov Decision Process based methodology to be used to evaluate the evacuation performance of an early stage ship design. From the literature study it was concluded that an evacuation process is a highly dynamic process. Two validation studies were performed to determine if a Markov decision process based approach can be used to assess the ships evacuation performance.

The first validation study demonstrated that the MDP model was able to differentiate, based on evacuation performance, between four rectangular rooms. Both the MDP method, as well as the methods used in the comparison study, determined that exits on all sides of the room evacuated the fastest. It is concluded that MDP model is able to identify an optimal exit configuration for a rectangular grid.

The second validation study concluded that the MDP model can differentiate between two decks of a naval ship design. The layouts were analyzed based on how quickly the majority of the population reaches an exit, how the exits are dispersed throughout the layout, how the population is distributed among the exits, and possible congestion locations. Taking the MDP model assumptions into account, evacuating a layout with a single passageway proved to be faster than with a double passageway. However, the latter showed to be more redundant to damage scenarios.

The extent to which the method can be used should be further investigated. As a result of the second validation study, where the model was be applied to a naval warship design, it is deemed probable that it can also be used for other complex ships, such as cruise ships and special purpose ships. This assumption should be investigated in further detail. An overview of the thesis findings are listed below:

- The relationship between a ships design and the evacuation performance is complex.
- Early stage ship design holds the most potential to improve the evacuation performance.
- The physical arrangement of a ship strongly affects evacuation process and efficiency.
- Exits that are evenly dispersed throughout the layout, and are located in accordance with the initial distribution, improve MDP simulation convergence and exit usage.
- An increase in the amount of evacuation analysis, both for passengers vessels as well as special purpose vessels, is expected due to regulation changes. This applies to ships constructed on or after 1 January 2020 and carrying more than 36 passengers, or 240 special personnel.
- The Markov decision process model shows potential to be used as a tool to differentiate between early stage ship designs.

8
Future work

Each variable used for input for any method influences the output and therefore conclusions drawn. Therefore, each input variable value should be justified. This thesis focuses on testing the potential of the MDP method. Further research should focus on justifying certain input values. The discount factor should reflect a persons short term goals and long term goals. The action probability could, for example, reflect a persons uncertainty in decision making. These aspects are further highlighted int his section. In short, this section are recommendations for future research in this method.

Improving model resolution
Currently the walls are included in the layout as states, in other words, only by adding a wall two states are disconnected from each other. This wall state shares the same geometric attributes as a regular state. Therefore, a course grid will result in unrealistic wide walls. A feature which is not incorporated, but could improve the models accuracy and running time, is to be able to remove edges between nodes in order to simulate a wall. This is graphically represented by Figure 8.1, and it can be seen that the layout is better represented if edges are simply removed.

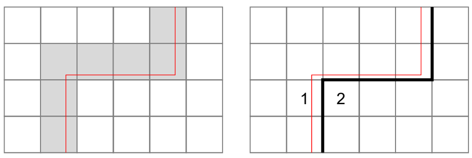


Figure 8.1: Example why removing edges will represent a layout better than wall states. Gray nodes are wall nodes, removing edge between state 1 and 2 will represent a wall

Multi-deck
Currently only one deck is simulated with the MDP-model, however the method could be used on a multi-deck layout. A stairway is added by linking all deck exits states with the corresponding adjacent deck exit states. Adding states in between the exit states can represent the time it takes to go up or a down a stairway. The amount of states could differ per exit type. The more states in between, the longer it takes for passengers to go up or down the stairways. Emergency station nodes should then have a positive reward instead of the exit locations to simulate occupants moving towards the emergency stations.

Modify utilities to including stability loss and initial population distribution
Two different proposals are made which were not yet investigate in more detail but could improve the MDP methodology. Firstly, the rewards in all states were kept the same, therefore the policies were also mainly a result of distance from an exit. The rewards could also be not all the same to create an asymmetrical utility distribution throughout the layout. For example, by setting negative rewards at port side lower than starboard, an incentive is created to move towards starboard side of the vessel. Since less negative rewards would increase the utility and therefore influence the policies. This transversely asymmetrical reward distribution would simulate a ship heeling. It is assumed people tend to

want to move upwards when a ship starts to heel. Since evacuations are done when the ship is in a critical state, stability loss should be incorporated in the simulations.

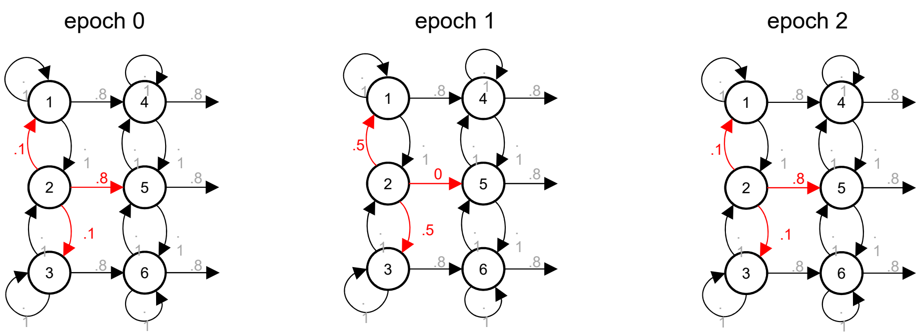
Secondly, the utility distribution used did not consider the initial distribution of evacuees. The same value was given to all state nodes whereas it would be more realistic to place more value on highly populated areas. Therefore, using the initial state distribution to scale the utility values accordingly would penalize populated areas further away from an exit. Similarly, non-populated isolated areas would be less valuated. Response time also differs for day and night scenario and by including the initial distribution a heavier penalty is given isolated accommodation areas far away from an exit.

Counter flow

In this thesis only one population was simulated. Therefore, the entire population used the nearest exit to egress towards to. As described by regulation, counter and cross flow should also be investigated. One way of doing this is to simulate the two populations separately and create two different Markov-Chain solution matrices, as given by Equation 3.8. The ratio between population sizes can be used to scale down both matrices according. For example, if the ratio between passengers and crew is 3 to 1, than this should also be reflected in both matrices. I.e. the passenger population is multiplied by .75 and the crew population by .25. These two solution matrices are then added together to create one solution matrix. An animation of this simulation is added in Appendix A.

State occupancy threshold

In order to limit the percentage of agents occupying one state, a state capacity limit could be introduced. If x% represents a person, then $4x$ could be a state capacity indicating only 4 persons per state is allowed. If a state is saturated, the transition probabilities to neighbouring states should be adjusted. This concept is further explained in this section.An illustration is given in Figure 8.2 for an arbitrary layout.



$$s_0 = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ \vdots \end{bmatrix} \quad M_0 = \begin{bmatrix} .1 & .1 & 0 & .8 & 0 & 0 & \cdots \\ .1 & 0 & .1 & 0 & .8 & 0 & \cdots \\ 0 & .1 & .1 & 0 & 0 & .8 & \cdots \\ 0 & 0 & 0 & .1 & .1 & 0 & \cdots \\ 0 & 0 & 0 & .1 & 0 & .1 & \cdots \\ 0 & 0 & 0 & 0 & .1 & .1 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} \quad s_1 = \begin{bmatrix} .1 \\ 0 \\ .1 \\ 0 \\ .8 \\ 0 \\ \vdots \end{bmatrix} \quad M_1 = \begin{bmatrix} .1 & .1 & 0 & .8 & 0 & 0 & \cdots \\ .1 & 0 & .1 & 0 & .8 & 0 & \cdots \\ 0 & .5 & .5 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & .1 & .1 & 0 & \cdots \\ 0 & 0 & 0 & .1 & 0 & .1 & \cdots \\ 0 & 0 & 0 & 0 & .1 & .1 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} \quad s_2 = \begin{bmatrix} .01 \\ .06 \\ .05 \\ .16 \\ 0 \\ .08 \\ \vdots \end{bmatrix} \quad M_2 = \begin{bmatrix} .1 & .1 & 0 & .8 & 0 & 0 & \cdots \\ .1 & 0 & .1 & 0 & .8 & 0 & \cdots \\ 0 & .1 & .1 & 0 & 0 & .8 & \cdots \\ 0 & 0 & 0 & .1 & .1 & 0 & \cdots \\ 0 & 0 & 0 & .1 & 0 & .1 & \cdots \\ 0 & 0 & 0 & 0 & .1 & .1 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

Figure 8.2: Arbitrary layout example changing transition matrix

The layout used is a 10x20 grid with no walls. The initial distribution is 100% at state 10 and is located at the bottom left corner. The exit node is state 191 and located at the top-right corner. An MDP is used to calculate all the policies and create a transition matrix, which is a 200x200 matrix. The action probabilities are .8 in the desired direction and .1 at perpendicular directions.

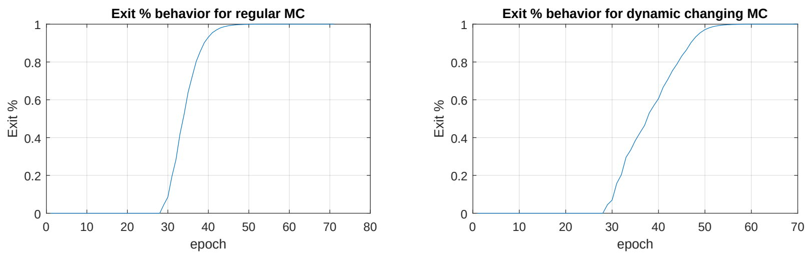


Figure 8.3: Exit % results for the regular and dynamic changing MC

The idea behind the method is, that when a state probability exceeds a threshold, all adjacent states with a policy to move towards the *'full'* state, are updated. The highest values are deleted (in the example $.8$ values are deleted) in the corresponding row of the transition matrix. The remaining values are adjusted accordingly so the sum of the row again equals 1. For example, if the remaining probabilities are $.1$ to the left and $.1$ to the right, then these are changed to $.5$ and $.5$. At each iteration all states exceeding the limit and all states below the limit are located. If the cell is below the limit than the adjacent state probabilities are reset. The exit behavior is plotted and given in Figure 8.3.

A

Appendix

A.1. Validation study 2 Exit results

	Case 1			
	Baseline		Variant 1	
Exit	**No1**	**No2**	**No1**	**No2**
1	.151 (4.5)	.737 (51.6)	.146 (4.4)	.761 (53.3)
2	.343 (10.3)	.099 (6.9)	.191 (5.7)	.054 (3.8)
3	.036 (1.1)	.058 (4.1)	.176 (5.3)	.074 (5.1)
4	.242 (7.3)	.038 (2.6)	.114 (3.4)	.039 (2.7)
5	.228 (6.8)	.050 (3.5)	.373 (11.2)	.060 (4.2)
6		.018 (1.3)		.012 (0.9)

Table A.1: Exit convergence results for case 1. In brackets the conversion to amount of crew.

	Case 2			
	Baseline		Variant 1	
Exit	**No1**	**No2**	**No1**	**No2**
1	.162 (4.9)	.515 (36)	.154 (4.6)	.505 (35.3)
2	.273 (8.2)	.081 (5.7)	.229 (6.9)	.058 (4.0)
3	.167 (5.0)	.062 (4.4)	.163 (4.9)	.099 (6.9)
4	.199 (6.0)	.267 (18.7)	.185 (5.5)	.261 (18.3)
5	.198 (5.9)	.055 (3.9)	.269 (8.1)	.064 (4.4)
6		.020 (1.4)		.014 (1.0)

Table A.2: Exit convergence results for case 2. In brackets the conversion to amount of crew.

		Deck No1		Deck No2	
Metric	**Case**	Baseline	Variant 1	Baseline	Variant 1
Std. Dev.	1	0.102 (1)	0.09 (0.88)	0.256 (0.96)	0.266 (1)
	2	0.04 (0.92)	0.043 (1)	0.175 (1)	0.17 (0.97)
95% mark	1/2	36 (0.88)	41 (1)	43 (0.64)	67 (1)
Sum normalized values		2.80	2.88	2.60	2.97
Difference			**+3.1%**		**+14.2%**

Table A.3: Comparison between standard deviation of final population distribution over exits and 95% mark. In brackets the normalized values which are summed to compare overall score

A.2. Maximum probability plots for the additional damage case

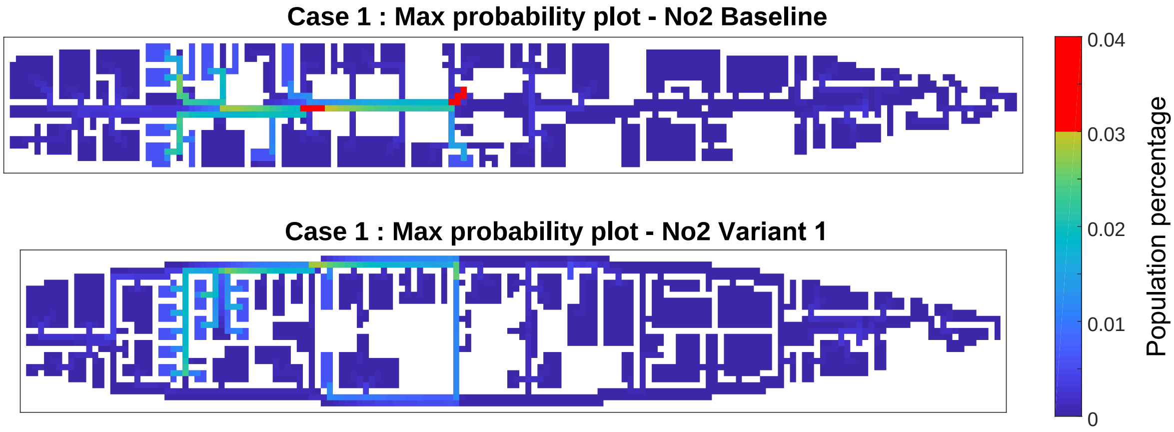


Figure A.1: Maximum probability plot for the night case of deck No2.

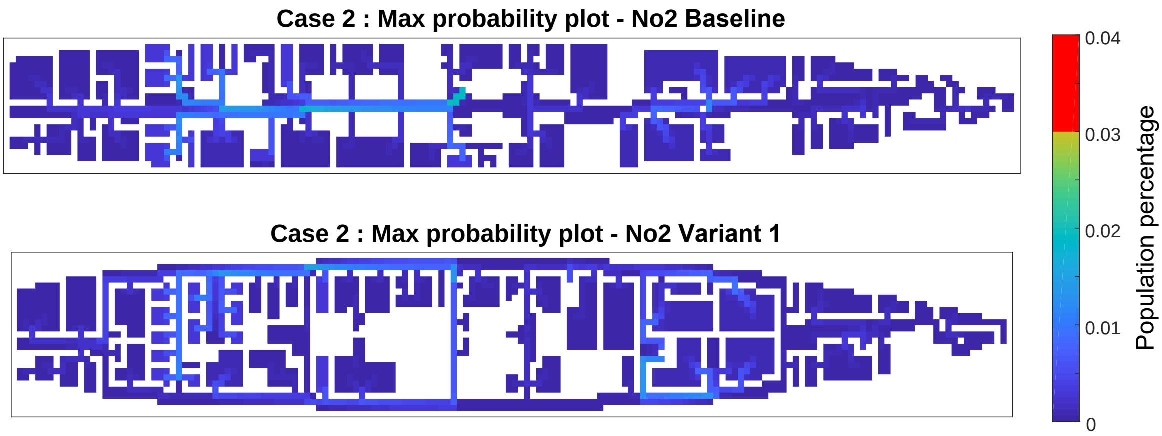


Figure A.2: Maximum probability plot for the day case of deck No2.

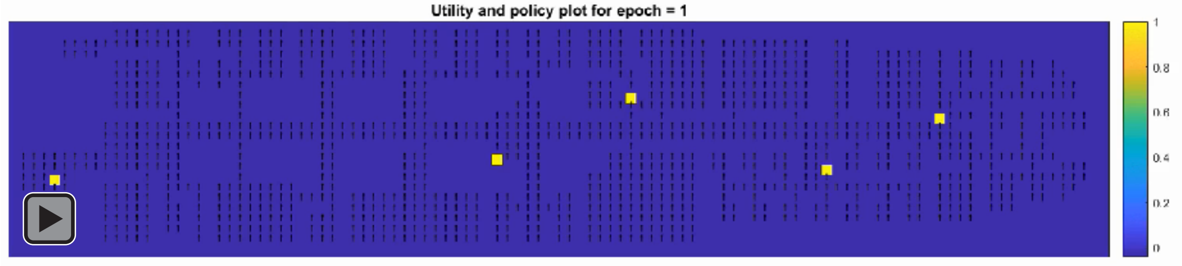
A.3. Value iteration code

```
    U = zeros(numStates,1,numActions);  %Initialize Utility matrix
    Q = zeros(numStates,1,numActions);  %Initialize Quality matrix
    numEpochs=100;
    discount = 0.95;
    global tmpPolicy;

    U_list=zeros(numStates,numEpochs);       %Save utility each iteration
    policy_list=zeros(numStates,numEpochs); %Save policies each iteration

% Solve MDP using value iteration
    for e=1:numEpochs
        for i=1:numActions
            %Calculate Quality matrix
            Q(:,1,i)=R+discount*P(:,:,i)*U(:,:,i);
        end
        %prepare for next epoch
        [U, tmpPolicy] = max(Q,[],3);

        % Reset exit utilities/rewards
        for i=1:length(exits)
            U(exits(i)==stateLoc)=exitR(i);
        end

        % Reset fire/hazard utilities/rewards
        for i=1:length(fires)
            U(fires(i)==stateLoc)=fireR;
        end

        % Update U matrix for next iteration
        for t=1:numActions/2
            U=cat(3,U,U);
        end

        % Safe solution to the list
        U_list(:,e)=U(:,1,1);
        policy_list(:,e)=tmpPolicy;
    end
```

A.4. Animation

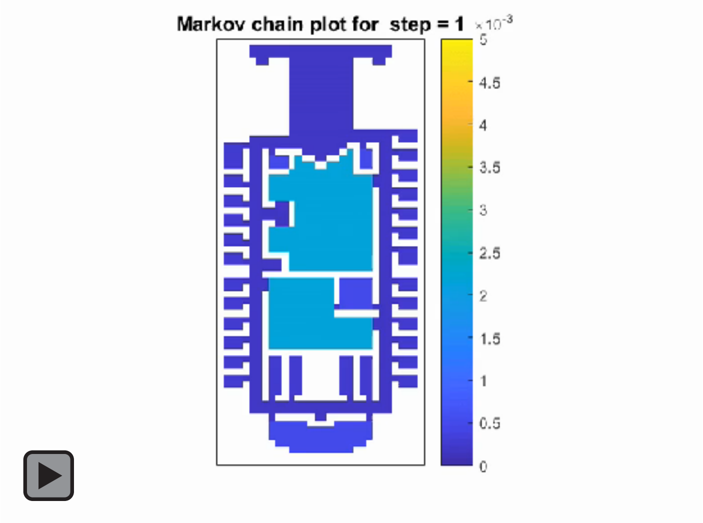
For the following animations a Adobe Flash plugin is required, an installation guide for Mac and Windows can be found on link. However, when this document is opened with Adobe Reader a pop-up should give information how to download the plugins.

Value iteration for No1 BL



Addition of two Markov chain solutions

Below an arbitrary layout is given where two Markov-Chain solutions have been added together and plotted. The first group consists of an population which has only access the bottom exits. The second group has been delayed for 40 steps and has access to all exits.



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