Impact of Safe Return to Port regulatory framework on cruise ship concept design

A software tool to mitigate design risks in early stages of the process

Alfredo Valcalda

TU Delft

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BY

Alfredo Valcalda

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THESIS COMMITTEE:	DR. IR. RG HEKKENBERG,	TU DELFT, CHAIRMAN
	DR. IR. A.A. KANA,	TU DELFT, UNIVERSITY SUPERVISOR
	IR. D. DE KONINGH,	DAMEN CRO, COMPANY SUPERVISOR
	DR. J. JOVANOVA, TU DELFT,	EXTERNAL COMMITTEE MEMBER
	DR. M. YANG, TU DELFT,	EXTERNAL COMMITTEE MEMBER

Abstract

The expansion of the cruise market in the last decades and the significant increase in the size of cruise ships, led to a revision of the safety standards for passenger vessels which resulted in the introduction of the so-called "Safe Return to Port" regulatory framework (SRtP). These regulations strongly impacted every aspect of the life of passenger ships, from commissioning to operations. Clearly also the design of these vessels was highly affected, inducing the design companies to face with the risks entailed by SRtP regulations on a daily basis. Indeed these regulations require great complexity of the systems in terms of redundancy and segregation, and their great interdependence further complicate the assessment of the functional capabilities requested by SRtP. The complexity required in the designs and the difficulties in assessing the compliance with the regulations contribute to increase the risks associated with SRtP projects. Obviously design companies are negatively affected by these risks and preventing expensive re-designs in later stages of the process is mandatory to improve the company's performance. Due to the complexity of the task, a support method for the mitigation of the risks entailed by the non compliance of the designs with SRtP regulations is proposed. The method comprises a through analysis of the spaces on board and a software tool to support designers in the assessment of the correct placement of the components of the systems, in order to guarantee the required capabilities in every casualty scenario.

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List of Abbreviations

- **AV**: Audio Visual;
- **CAD**: Computer Aided Design;
- **CFD**: Computational Fluid Dynamic;
- **COG**: Centre Of Gravity;
- **CRO**: Cruise, Ro-pax and Offshore;
- **CS**: Classification Societies;
- **D&P**: Design and Proposal;
- **EER**: Evacuation, Escape and Rescue;
- **EMC**: Electromagnetic Compatibility;
- **EMI**: Electromagnetic Interference;
- **EN**: Equipment Number;
- **ER**: Engine Room;
- **F&F**: Fixed and Firm;
- **FB**: Free Board;
- **FCA**: Functional Chain Analysis;
- **FEA**: Finite Element Analysis;
- **FFF**: Fixed Fire Fighting system;
- **FMEA**: Failure Mode and Effect Analysis;
- **FTA**: Fault Tree Analysis;
- **GA**: General Arrangement;
- **GP**: General Particulars;
- **GT**: Gross Tonnage;
- **HVAC**: Heating, Ventilation and Air Conditioning;
- **IAMCS**: Integrated Alarm Monitoring and Control System;
- **IMO**: International Maritime Organization;
- **IT**: Information Technology;
- **LFT**: Location Fault Tree;
- **LOI**: Letter Of Intent;
- **LSA**: Life Saving Appliances;
- **MSB**: Main Switchboards;
- **MSC**: Maritime Safety Committee;
- **MVZ**: Main Vertical Zone;
- **NT**: Net Tonnage;
- **Nav & Naut**: Navigation systems (radar, GPS, DP...);
- **OPV**: Ocean Patrol Vessel;
- **RFI**: Request For Information;
- **RFP**: Request For Proposal;
- **RFQ**: Request For Quotation;
- **ROM**: Rough Order of Magnitude;
- **SRtP**: Safe Return to Port;
- **TR**: Temporary Refuge;
- **UPS**: Uninterruptible Power Supply;

1
Introduction

1.1. Background

In the past decades, the cruise ship industry experienced a phenomenal growth. Over the last ten years the number of passengers increased by over 50% and it was still expected to grow in the coming years according to the 2018 Market Forecast Report of Sea Europe Shipyards'& Maritime Equipment Association [58] before the tourism crisis caused by Covid-19 in 2020. The expansion of the cruise tourism has led to a rapid surge, not only in vessel number but more markedly in vessel capacity [57]. With the growth of the number of passengers on a single vessel, also the risk associated to this branch of the shipping industry increased. For this reason, the regulatory institutions started questioning if the current safety standards were sufficient for these new gigantic and ever more sophisticated ships. As a result of a review of the regulations started in early 2000's the International Maritime Organization (IMO), during its 82^{nd} session in 2006, approved a package of amendments to regulations dedicated to large passenger ships [45]. These regulations are commonly known as "Safe Return to Port" (SRtP) requirements.

1.2. Problem introduction

"Safe Return to Port" caused a dramatic revolution not only in the shipbuilding industry, where the changes in the ships architecture led to the need to rethink the conventional design procedures [68], but also in the operations and in all the other aspects of the life of a passenger vessel. Even if mega-cruise ships were originally the target of Safe Return to Port framework, it is argued that the biggest impact of these regulations has been on the design of small and medium size passenger ships [67]. In fact, totally new arrangements had to be developed for these vessels, while larger ships were already designed with many of technical solutions required by SRtP regulations (e.g two separate engine rooms). It follows from above that the introduction of the SRtP framework significantly affected the business of ship-owning companies, shipyards and, above all, design companies. In this context, DAMEN CRO (Cruise, Ro-pax and Offshore) is a design company of the DAMEN group that focuses on the design of ro-pax vessels and small to medium size cruise ships. Indeed, Safe Return to Port regulations pose an everyday challenge to the designers at DAMEN CRO, who face with the risks entailed by these regulations on a daily basis.

1.3. Research objective and research questions

From the Problem Introduction, the following research objective is formulated:

Develop a method to mitigate the risks entailed by Safe Return to Port regulatory framework, in order to prevent significant re-designs of the vessel in a late design stage costing valuable time and money due to the non-compliance with SRtP regulations that could have been covered in an early design stage.

To effectively meet the objective of the thesis project, the following research questions and subquestions will be addressed:

- *What is the Safe Return to Port regulatory framework?*
  - *Why was it necessary?*
  - *What are the innovations encompassed?*
  - *What are the intentions, goals and concepts of these regulations?*
  - *What are the consequences of their implementation?*
  - *Are there similar safety strategies in other industries?*
- *How does the design process work?*
  - *How does the generic design process work according to literature?*
    - *What are the risks in the design process?*
  - *How does the design process for SRtP vessels work according to literature?*
    - *What are the challenges in designing SRtP vessels?*
  - *How does the design process for SRtP vessels work in DAMEN?*
  - *When in the design process is it better to mitigate risks?*
- *How can the risks in the process entailed by SRtP regulations be efficiently mitigated?*
  - *What is the best method to mitigate these risks?*
  - *What are the requirements for such a method?*
  - *How can the method be validated?*

In this report the above questions will be answered through the chapters and the solution to meet the research objective will be presented.

1.4. Solution proposed

The solution for the mitigation of the risks entailed by SRtP regulations in the design of passenger ships, developed to meet the goal of the thesis, consists in a support method for the assessment of the compliance of the systems on board. The method comprises two parts: the definition of the spaces on board and the evaluation of the required level of survivability of the systems by means of a software tool. The space definition is necessary to identify all the characteristics of the spaces in which the different systems are placed while the software tool is meant to assess the achievement of the compliance of the systems. The goal of the assessment tool is to verify that all the components of the systems are positioned in such a way that the functional capabilities required by SRtP are granted in every casualty scenario. The method is designed to be applied since the beginning of the process, in order to mitigate the risks of non-compliant solutions in the design and to support the engineers during the design of these complex vessels. In this report a complete walk-trough of the development of the proposed solution is provided. All the relevant steps of the graduation project, from the literature review to the application of the method in the case study, are described to guide the reader through the work of this thesis.

1.5. Structure of the report

In the following chapter the genesis of Safe Return to Port regulations, the change in the regulatory philosophy and the main differences between these rules and the conventional regulations are described and discussed. Chapter 3 gives a complete overview on the Safe Return to Port framework analysing intentions, concepts and impacts of the regulations in question. In Chapter 4 a focus on the design process is presented. First, the general design process for ships according to the literature is introduced, then the design process related to SRtP projects and subsequently the specific design process for passenger ships applied by DAMEN CRO. In Chapter 5 the problem of the thesis is defined, a method to mitigate the risks is drafted and the requirements of such a method are delineated. In Chapter 6 different approaches available in literature are discussed and compared to consider a possible application in the solution of the research goal. In Chapter 7, the main concepts and features of the proposed method are described. In Chapter 8 all the tasks performed during the Proof of Concept phase are reported and a small scale model developed for this phase is explained. Chapter 9 and Chapter 10 focus on the large scale model developed for the thesis project. Chapter 9 describes the assessment performed by the tool and in Chapter 10 the design solution proposed by the software are analysed. In Chapter 11 is reported the testing strategy elaborated for the correct validation of the large scale model while Chapter 12 focuses on the Case Study. In the final chapter (Chapter 13) conclusions about the graduation project are drawn and ideas for the further development of the model are examined.

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Evolution of the regulations for passenger ships

In this chapter the philosophy, goals and results of the IMO Passenger ship Safety Initiative are described. The impact of the decisions carried out during this initiative to the regulatory sector are also mentioned in Paragraph 2.2. In Paragraph 2.3 and 2.4 the literature available on the different types of regulations is analyzed.

2.1. The IMO Passenger Ship Safety Initiative

The phenomenal growth that the cruise industry witnessed has deeply altered the fundamental nature of passenger shipping[44]. These unprecedented developments in the cruise market inevitably caused an increase of the risk connected to this branch of the maritime industry, particularly in relation to the number of passengers carried on a single vessel. Questions about the safety of these new massive vessels started to arise, in particular, on how quickly these mega-ships could be evacuated in an emergency and whether search and rescue services (SAR) were capable of effectively rescuing thousands of persons from survival crafts [44]. For these reasons a complete review of passenger ship safety started in 2000, with the aim of evaluating if the regulations were adequate for these new large passenger vessels [46]. With the purpose of facilitating deliberations on this complex issue, the IMO established a guiding philosophy and strategic goals to be achieved, in order to assist the Working Group in its evaluation. Below the guiding principles are reported from the paper "The IMO Passenger Ship Safety Initiative":

- *The regulatory framework should place more emphasis on the prevention of a casualty from occurring in the first place.*
- *Future passenger ships should be designed for improved survivability so that, in the event of a casualty, persons can stay safely on board as the ship proceeds to port.*

- *The regulatory framework should permit alternative designs and arrangements in lieu of the prescriptive regulations provided that at least an equivalent level of safety is achieved.*
- *Passenger ships should be crewed, equipped and have arrangements to ensure the safety of persons on board for survival in the area of operation, taking into account climatic conditions and the availability of SAR functions.*
- *Passenger ships should be crewed and equipped to ensure the health-safety, medical care and security of persons on board until more specialized assistance is available.*

After six years of complex and extensive deliberations, the new drafted rules were adopted at MSC 82 in November 2006: the Safe Return to Port regulations (SRtP). These new regulations deeply changed the concept of safety in the whole maritime sector, not only introducing totally new concepts like "safe return to port","safe areas" or "casualty threshold", but especially introducing an entirely new regulatory philosophy for the design, construction and operation of passenger ships: a *proactive* approach to safety [44].

2.2. From reactivity to proactivity

Most of the international shipping regulations have been developed in reaction to casualties in order to prevent similar accidents from occurring again. A notorious example is the establishment of the International Convention for the Safety of Life at Sea (SOLAS) itself, that has been developed in response to the infamous disaster of the RMS Titanic in 1912 [47]. This reactive philosophy characterized the work of the regulatory authorities since their establishment. In the recent years however, increasing importance has been given to change this philosophy guiding the work of the institutions, from reactivity to proactivity. As defined by Psaraftis [52], proactivity means *an early stage identification of factors that may adversely affect maritime safety and immediate development of regulatory action to prevent undesirable event.* An evidence of this change in direction are the goal-based standards, which gained more and more importance in the regulatory domain. Indeed, goal-based or performance standards are intrinsically proactive [60]. In fact, this type of safety requirements needs an in-depth analysis of the goal to be pursued, and this analysis requires an extensive knowledge of all the aspects which may affect the achievement of the goal.

2.3. From Prescription-based standards to Goal-based standards

A significant revolution made by the International Maritime Organization throughout the review mentioned in the previous paragraphs, consisted in the decisive change of direction in the methodology of defining safety standards, from prescriptive to goal-based. According to Hamann and Peschmann [23], the basic idea behind Goal-Based standards is the replacement of a system of prescriptive regulations representing an unknown and not quantifiable safety level by a system specifying goals and functional requirements. Goal-Based regulations set safety goals and do not specify the means of achieving the goal, allowing alternative ways to obtain the compliance. In the paper "Goal-Based standards - A new approach to the international regulation of ship construction" by H. Hoppe [26], the author makes an example to better explain the difference between prescriptive and goal-based regulations. To secure the edge of a cliff, the prescriptive regulation would mandate: "you shall install a 1 meter high rail at the edge of the cliff". For the same scenario, the goal-based regulation would prescribe: "people shall be prevented from falling over the edge of the cliff", leaving to the authority the choice of the technical solution to implement in order to meet the requirement.

2.4. Goal-Based regulations vs. Prescription-based regulations

As it should be clear from the example reported above, Goal-Based regulations give greater freedom in developing technical solutions and accommodating different safety standards, while prescriptive regulations are unable to cope with a diversity of design solutions. Furthermore prescriptive regulations, the majority of which has been developed in the aftermath of past experiences, encode the best engineering practice at the time they are written, but they tend to become less and less relevant over time and eventually to become deficient when the best engineering practice changes, for example due to the progress of the technologies [26]. For these reasons, Goal-Based regulations are considered essential to stimulate innovation [26] [51] [35] [49]. For Papanikolaou (2009), Goal-Based regulations also give the possibility of optimizing the ship performance, since no regulatory constraint is determined by prescriptive rules. As it can be seen in Figure 2.1, prescriptive regulations might not be effective or optimal for every type of design since the best design solution may lie outside the regulatory envelope.

Goal-Based regulations however, have also drawbacks. For example, while prescriptive regulations are quick and straightforward to apply, the implementation of performance standards usually requires more work from engineers and designers. Vassalos (2009) asserts that designers are finding it rather difficult to move away from the prescriptive mindset that has been deeply ingrained in their way of conceptualising, creating and completing a ship design. Hamann and Peschmann (2013) claim that some stakeholders are even reluctant to accept this innovation in the regulatory philosophy due to the increase of the engineering effort that Goal-Based regulations entail. Furthermore, even when it comes to verify the compliance of the designs, prescriptive rules are preferred. Unlike with prescription-based designs, the compliance of goal-based designs must be verified with a time and resource consuming process. The classification and approval of the designs results in uncertainties during the design process, and represents another reason of the stakeholders' hesitation

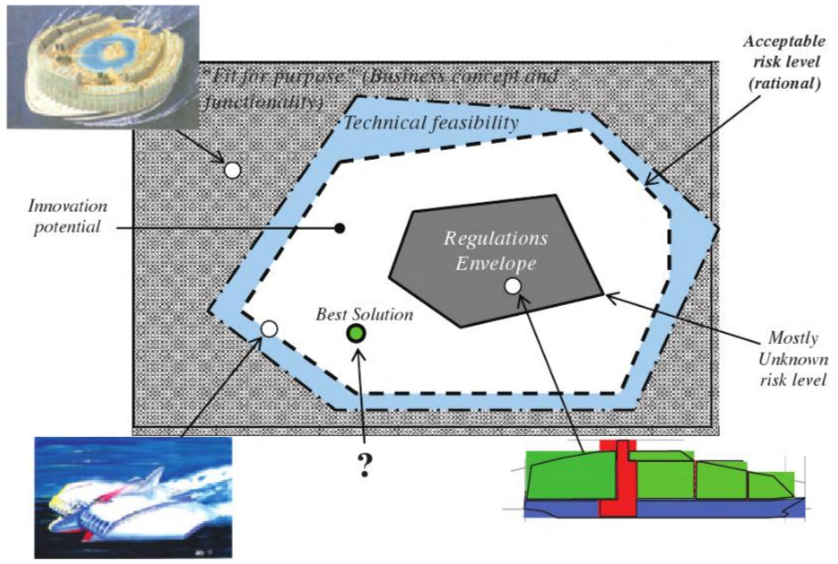

Figure 2.1: Possible design solution envelopes (Papanikolaou 2009)

in completely accepting these type of regulations [23]. An additional challenge that often designers and engineers have to face while dealing with performance requirements is the ambiguity in their formulation. The ambiguity, for example in the case of SRtP requirements, is deemed necessary to cater for the many different types of ships operating in very different circumstances as Dodman (2010) explains.

3

Safe Return to Port

In this chapter an overview of the concepts, objectives and safety performance standards of the Safe Return to Port regulations is provided.

3.1. Intentions of Safe Return to Port regulations

The overall intention of these regulations is to increase the safety of passenger ships in case of fire and flooding casualties and to reduce the likelihood of evacuation following the concept that the ship itself is the best lifeboat. The vessel should be able to return to a safe port nearby without any external help and a minimum level of survivability must be granted in safe areas on board while returning to port. The rules outline two scenarios:

- **Safe Return to Port**[27] [29], with a fire or flood casualty (within a defined threshold) the ship should be able to return to a safe port with its own power.

- **Orderly Evacuation and Abandonment of the ship** [28], if the casualty exceeds the defined threshold the ship should maintain the capability to permit the passengers to evacuate and abandon the ship.

Even if the second situation, in principle, could not be defined as "Safe Return to Port", it is described in the same regulations and it is generally included in the "SRtP framework". Figure 3.1 outlines the two situations above mentioned: the Safe Return to Port scenario (green box), for a casualty within the defined threshold and the Orderly Evacuation and Abandonment of the ship (red box) for a casualty exceeding the defined threshold. These concepts will be further explained in this chapter.

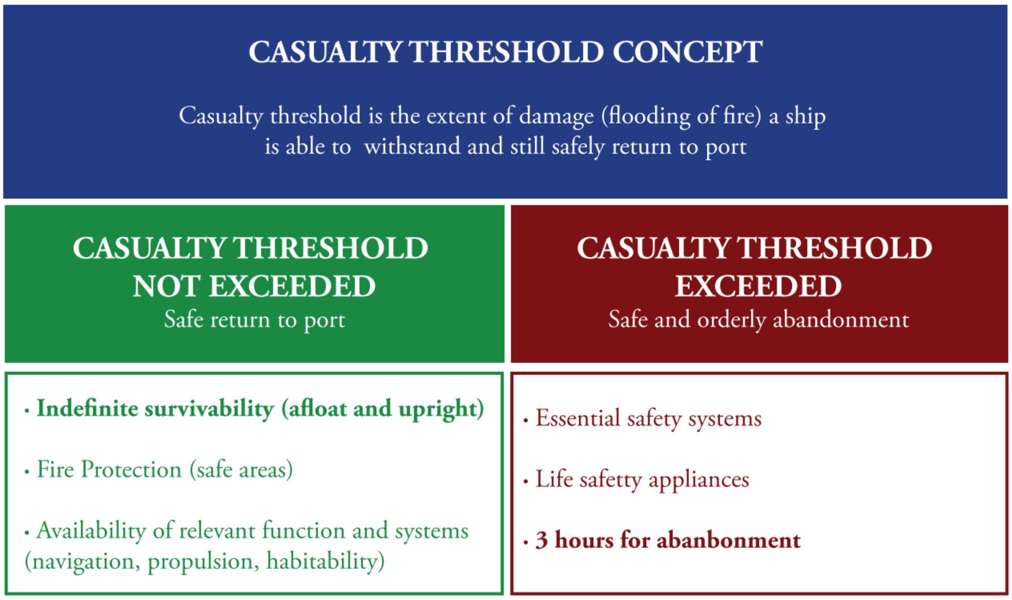

Figure 3.1: The IMO Framework – Passenger Ship Safety (Vassalos 2009)

3.2. Reference documents

The Safe Return to Port regulations are contained in multiple documents. Moreover, different IMO circulars containing guidelines for the application and interpretations of SRtP requirements have been issued, with the aim of clarifying every single aspect of these regulations. The reference documents SOLAS are:

- Reg. II-1/8.1.2 [29]: Availability of essential systems in case of flooding damage;
- Reg. II-2/21 [27]: Casualty threshold, safe return to port and safe areas;
- Reg. II-2/22 [28]: Design criteria for systems to remain operational after a fire casualty;

The relevant IMO circulars are:

- MSC.1/Circ. 1369 [32]: Interim explanatory notes for the assessment of passenger ship systems' capabilities after a fire or flooding casualty;
- MSC.1/Circ. 1368 [31]: Interim clarifications of SOLAS chapter II-2 requirements regarding interrelation between the central control station, navigation bridge and safety centre;
- MSC.1/Circ. 1291 [30]: Guidelines for flooding detection systems on passenger ships;

3.3. Applicability

The Safe Return to Port regulations apply to all passenger ships with a length of 120 meters or more or with at least three Main Vertical Zones (MVZ)[1], having their keel laid after July 2010 [45]. These regulations are also applicable to special purpose ships intended to carry more than 240 persons in total [9]. Furthermore, naval vessels that are constructed in compliance with the naval ship code ANEP 77 are required to fulfill a set of requirements that basically are equivalent to the SOLAS regulations for fire casualties in the SRtP scheme [10].

3.4. SRtP concepts

The Safe Return to Port regulations introduced some totally new notions and concepts to describe the safety standards [3]. In this chapter, the meaning of these notions, in the context of SRtP requirements, will be explained.

3.4.1. Casualty Threshold

As defined in SOLAS [27], the casualty threshold is *"the maximum extent of an incident of fire or flooding where the ship shall be able to return to port under its own power"*.
Two casualty scenarios are mentioned and two different casualty thresholds are defined.

Flooding scenario
Regulation 8-1 in Chapter II-1 Paragraph 2 states:

"A passenger ship shall be designed so that the systems specified in regulation II-2/21.4 remain operational when the ship is subject to flooding of any single watertight compartment."

Watertight compartment refers to any space below the bulkhead deck within watertight boundaries. Watertight compartments in which the risk of flooding originating is negligible do not need to be considered as compartments of origin of a flooding. In this regard, Germanischer Lloyd in the “Preliminary Guidelines for Safe Return to Port Capability of Passenger Ships” [36] suggests that such compartments include, but may not be limited to:

- compartments located from the shell side at least B/10 and from the bottom at least B/20,
- compartments not crossed by seawater piping systems,
- compartments not containing drainage piping systems collecting external waters.

Furthermore, when crossed by piping systems other than stated above, the impact and consequences of the available fluid quantity susceptible to flood the compartment are to

[1] According to SOLAS II-2 Regulation 3.32, Main Vertical Zones are those sections into which the hull, superstructure and deckhouses are divided by "A" class divisions, the mean length and width of which on any deck does not in general exceed 40 m

be assessed [36]. In the flooding scenario it is assumed that the cause of the casualty is internal, hence hull penetration with consequential damage and flooding is not considered to be within the threshold [11].

Fire scenario
The casualty threshold in the context of fire is described in Regulation 21 in Chapter II-2 Paragraph 21.3 [27] as:

– *loss of space of origin up to the nearest "A" class boundaries, which may be a part of the space of origin, if the space of origin is protected by a fixed fire-extinguishing system; or*

– *loss of the space of origin and adjacent spaces up to the nearest "A" class boundaries, which are not part of the space of origin.*

"A" class boundaries, as defined in SOLAS Chapter II-2 Reg. 3.2, refers to "A" class divisions formed by bulkheads and decks. A visual representation of the fire casualty threshold is provided in Figure 3.2, in which it is possible to notice how the fire is considered to spread to adjacent compartments, with and without fire-extinguishing system, according to the regulations. As in the case of flooding casualty, spaces in which the risk of a fire originating is negligible need not be considered as spaces of origin of a fire. A list of these can be found in "Rules for Classification and Construction- Preliminary Guidelines for Safe Return to Port Capability of Passenger Ships" by Germanischer Lloyd [36].

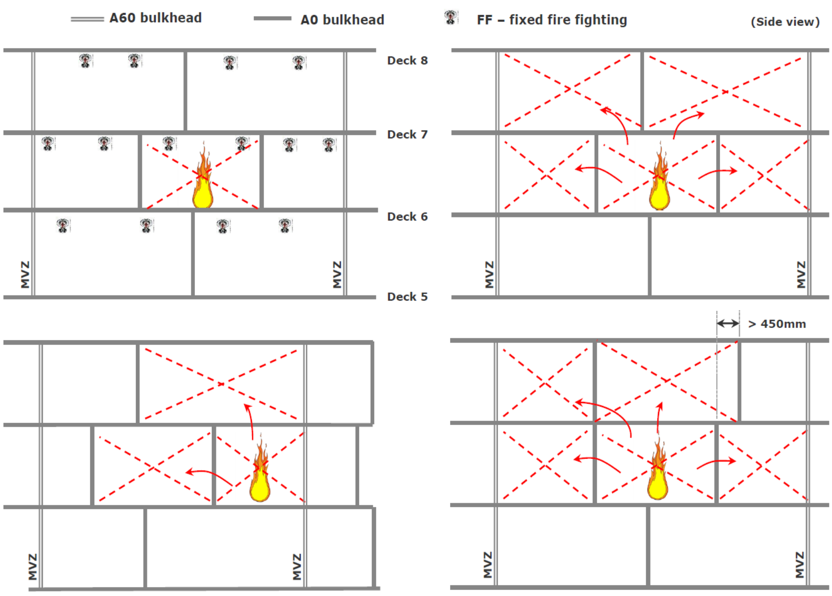

Figure 3.2: The Fire Casualty Threshold – Introduction to Safe Return to Port (DNV GL, Karl Hovden, 2017)

3.4.2. Safe Areas

SOLAS II-2 Reg. 3.51 defines the notion "Safe Area" in the context of a casualty as:

"*any area(s) which is not flooded or which is outside the main vertical zone(s) in which a* *fire has occurred such that it can safely accommodate all persons on board to protect them from hazards to life or health and provide them with basic services.*"

The basic services necessary to ensure the health of all persons on board mentioned in the definition are [45]:

- *Sanitation;*
- *Water;*
- *Food;*
- *Alternate space for medical care;*
- *Shelter from the weather;*
- *Means of preventing heat stress and hypothermia;*
- *Light;*
- *Ventilation.*

Safe areas can be separated, provided the required basic services are available for all persons on board. Interpretation 42 of Circ.1369 [32] requires a minimum space of 1 square meter per person for a SRTP operation shorter than 12 hours and 2 square meters per person for longer operations. According to Bureau Veritas Rule Note 598 [67] Paragraph 3.1: *“The area to be taken into consideration for the sizing of the safe areas should not include the areas occupied by fixed furniture such as desks, bars etc”.* An important issue related to the safe areas is the requirement asking for access to life-saving appliances which shall be ensured for every safe area taking into account that internal transit through the affected main vertical zone might not be possible.

3.4.3. Essential systems

Essential systems are listed in SOLAS II-2 Reg. 21 paragraph 21.4 [27]. These systems are:

- *Propulsion;*
- *Steering systems and steering-control systems;*
- *Navigational systems;*
- *Systems for fill, transfer and service of fuel oil;*
- *Internal communication between the bridge, engineering spaces, safety centre, fire-fighting and damage control teams, and as required for passenger and crew notification and mustering;*
- *External communication;*
- *Fire main system;*
- *Fixed fire-extinguishing systems;*
- *Fire and smoke detection system;*
- *Bilge and ballast system;*

- *Power-operated watertight and semi-watertight doors;*
- *Systems intended to support "safe areas" as indicated in paragraph 5.1.2 (SOLAS II-2 Reg. 21);*
- *Flooding detection systems;*
- *Other systems determined by the Administration to be vital to damage control efforts.*

These systems are required so to ensure propulsion and maneuverability after a casualty not exceeding the casualty threshold, to maintain safety in all parts of the ship not affected by the casualty and to ensure services needed to be available in safe areas.

3.4.4. Orderly Evacuation

SOLAS II-2 Reg. 22 [28] describes the performance requirements the ship must grant if the casualty threshold is exceeded. In this scenario, the systems listed below must remain operational for at least three hours after the casualty occurs, in all Main Vertical Zones not affected by the casualty:

- *Fire main;*
- *Internal communications (in support of fire-fighting as required for passenger and crew notification and evacuation);*
- *Means of external communication;*
- *Bilge systems for removal of fire-fighting water;*
- *Lighting along escape routes, at assembly stations and at embarkation stations of life-saving appliances;*
- *Guidance systems for evacuation.*

To achieve the above requirement, Bureau Veritas Rule Note 598 in paragraph 4.4 [67] suggests that the main and emergency sources of electrical power should be distributed in at least two separate main vertical zones. Moreover, proper distribution of pumps for fire main and bilge systems will have to be taken care of, as well as careful routing and protection of concerned piping and cables.

3.5. Impact of SRtP regulations

Safe Return to Port regulations has had indeed a considerable impact on the design of large and medium size passenger vessels, but it is not limited to this. Repercussion of these regulations can be found in every aspect of the life of these ships, from the commissioning to the operations and both operators and shipyards in the cruise industry are still evolving their response to meet the regulatory requirements [13]. An overview of the largest consequences of SRtP regulations is provided in this section.

3.5.1. Impact on Ship Design

The change in perspective of passenger ships' design, induced by the new regulations, caused a dramatic revolution of the design procedures [6]. It is known that the traditional design process for many conventional types of ships is based on the imitation of existing designs with small adaptation from case to case [50]. The introduction of SRtP requirements, as it is clear from the above paragraphs, revolutionized the architecture of passenger ships, leading to the need to rethink the whole design process. Vicenzutti et al. (2016) distinguish two levels of impact on ship design: direct impact and indirect impact.

Direct Impact

The direct impact can be summarized as the need to redesign certain systems in order to meet the compliance with the requirements. The goal of the SRtP rules, i.e. assuring the operation of the essential systems after a casualty, deeply altered not only the systems architecture, but also the systems spatial placement, causing a significant rise in design complexity. The design of the power system is a clear example of what has been just described. As for other systems, the compliance can be achieved with the separation criteria. However,the location of several electrically powered systems on board is fixed by their function and by the ship's architecture. Indeed, part of the propulsion system (e.g. bow thrusters) needs to be placed on ship's bow to allow the correct operation of the ship, and must function in spite of a casualty. To achieve this, both power system sections have to cross the entire ship side-by-side to power the thrusters. This implies an increased difficulty in ensuring the required levels of separation and duplication, along with the need of focusing on spatial placement of all the power system elements, cables included, which was not a priority before SRtP.

Indirect Impact

The indirect impact of SRtP requirements on ship design lies in the need of demonstrating the compliance with the regulations to all the stakeholders. Even if the design of a "SRtP ship" is difficult, it is not the sole complex task that designers have to face. The compliance of the designs must be demonstrated and designers are interested in performing this verification process by themselves, instead of totally relying on the Classification Societies, in order to avoid the possibility that the design will be eventually rejected.

3.5.2. Impact on Shipbuilding

As described in the above paragraph, the designers had to make a considerable effort to comply with the new regulations. Clearly, the additional complexity of the design made the ships ever harder to build as well. From an economic point of view, the effort in the design process first and in the construction phase then, affected the costs of new ships' orders [34]. In addition to the rise in complexity, the shipbuilders faced another issue which resulted in additional costs: the increase of materials in terms of quantity and quality. In fact, the effective redundancy imposed by goal-based regulations required more systems to be installed on-board, as well as more components for every system. According to Miller et al. (2011), additional building cost arises from more equipment, routing design, cabling and electrical components, piping & valves and also crew training. To give an indication of the increase of shipbuilding costs, some approximate data was asked at the Company. Compared to a ship without any redundancy implemented (e.g. no separated engine room), the cost of the vessel is deemed to increase by 8-10%. For a more common situation, where some design solutions to enhance redundancy have already been implemented, making the ship SRtP compliant would increase shipbuilding costs by 4-6%. If it is considered a range of value of the ships DAMEN usually works with, from 70 millions for small Ro-Pax vessel to 300 millions for larger cruise ships, it can be claimed that the increase of shipbuilding costs caused by the introduction of this regulatory framework is in a range between few millions (best scenario and least expensive projects) and tens of millions for expensive projects with no redundancy solutions implemented.

3.5.3. Impact on Operations

As mentioned in the introduction of this section, the SRtP rules affected other aspects of the life of a passenger, not only the design phase. An example reported in Cangelosi et al. (2018) is the maintenance of the systems of ships that must comply with SRtP regulations. In fact, when important pieces of machinery are supposed to be under maintenance during navigation, it may affect the compliance with SRtP requirements due to the unavailability of the necessary redundancy. Even if currently there are no clear indications in the rules on the matter, this is an evident example of how these regulations can also impact the operational life of the vessel. Another important implication of these rules during the operational life of the ship is the training of the crew. Safe Return to Port regulations allow manual intervention to restore the capabilities of essential systems after a casualty. For this reason, the personnel on board should be highly qualified and well trained for this potential event [63]. Documentation and the operational manuals are required by the SRtP rules, but as the Class Guidelines of DNV GL [9] suggests, regular training for the crew should be performed, since the SRtP operations will never or very rarely be needed in practice, and therefore the crew will gain very limited practical training.

3.6. Safe Return to Port safety concepts in other industries

Every industry has its own peculiarities and, in every sector, different hazards pose diverse challenges to the safety of people. Despite this, disparate fields may be influenced by safety strategies applied in another sector, and many similarities among the concepts and approaches in different fields can be found. It is argued for example, that some of the safety guidelines in the maritime industry, especially those regarding evacuation, derive from civil engineering [33]. In this section, the literature about safety strategies is reviewed in order to find analogies with SRtP concepts and to explore how different industries deal with similar casualty scenarios.

3.6.1. Civil engineering

The first similarity between SRtP rules and the regulations in the building sector is the recent shift from prescriptive to performance based requirements. As in the cruise industry, also in the civil field this shift was necessary to follow the technology progress in the sector. As for the new massive cruise ships, the "one-size" prescriptive regulatory framework was not suitable for scenarios so complex and unique like mega-tall buildings [7]. In addition to the same regulatory philosophy, analogies between Safe Return to Port regulations and the rules of the building industry can be found also in safety concepts and emergency strategies.

Protect-in-place or Shelter-in-place concept

The Protect-in-place or Shelter-in-place concept is evidently the closest to the SRtP intent of making the ship the safest place to stay in case of emergency. According to this approach, occupants of a building should remain in the area enclosed to fire rated construction or move to such a location instead of evacuating the structure [41]. The protect-in-place strategy is commonly used in high-rise buildings. In fact, the taller the building, the greater the possibility of a fire occurring on an upper floor and people being trapped above the fire floor [48]. According to Bukowski 2009, tall buildings must be provided with refuge floors every 20/25 floors. These "safe areas" for skyscrapers, should not be normally occupied spaces, large enough to hold all occupants of the floors between refuge floors and they must follow additional requirements to support life during a fire emergency (e.g must be open on two opposite sides so that smoke will not accumulate). The protect-in-place approach is especially important for mobility impaired individuals and is therefore a very common safety strategy in healthy care facilities, where critically ill or injured patients cannot easily exit or leave the building. For this reason, hospitals are designed to support protect-in-place fire emergency strategy, minimizing the need to evacuate and, to the extent possible, allow for patients to remain in place or relocate within the building [38]. If people have to remain in the building, it is essential to contain the fire and to prevent structural collapse. To protect the occupants for the duration of the incident from fire and smoke spread, building construction and fire protection systems are employed. Shelter-in-place strategy is also applied in case of chemical, biological, or terrorist threats [65].

Other similar concepts in the building industry

Other Safe Return to Port notions can be connected to safety concepts employed in the building industry. For example, the "building performance" concept resembles the SRtP requirement that expects the ship to be able to operate with a casualty within the threshold. According to Cowlard et al (2013), building performance concerns the time that the structure can withstand the effects of the fire and the compartmentation remain in place and functional. This is fundamental for example during "phased evacuation", when people are organized and periodically evacuated according to a priority strategy. Since this type of evacuation takes more time than the standard "simultaneous evacuation" [21], it is clear that the integrity and the functionality of the compartments not affected by fire casualty has to be preserved until the abandonment of the building is completed. The "phased evacuation" emergency strategy resembles the "orderly evacuation" scenario prescribed by Safe Return to Port regulations.

3.6.2. Other industries

Similar emergency response strategies can be found in other industries. For the off-shore sector, for example, escaping from a platform is considered a potentially dangerous action and it is claimed that evacuation, escape and rescue (EER) operations have often failed in major accidents [59]. For this reason, for modest casualty scenarios (e.g. leakage of toxic gases on the platform), it is wise not to expose the crew to possible hazards and keep it safe on the structure. In any casualty scenario however, a Temporary Refuge (TR) must be available and it must provide life support for a period of time until complete evacuation can occur [16].

In a totally different environment, namely urban and wild land fires, a similar protect-in-place strategy is employed. Since it has been observed that an high proportion of the deaths due to bonfires in Australia were people either being outside and exposed to radiant heat or occurred in vehicles while evacuating [25], defend-in-place is now considered a valid emergency strategy [62]. In this case, well-prepared houses that can be successfully defended from bushfires act as "safe area", and it is meant to provide refuge for people during the passage of the fire front.

3.6.3. Considerations on safety strategies in different industries

Reviewing the literature about the safety strategies applied in different industries, many similar concepts and approaches have been found. This review highlighted a considerable research about the movement of people in emergency situations (e.g. evacuation or studies on how to reach safety areas in protect-in-place strategies), as well as a good knowledge on the emergency measures necessary to protect people in safe areas. Instead, less papers focus on the performance of the structure and on the reliability of the systems in case of casualty scenarios, mainly analysing the capability of HVAC system in the building industry and the structural integrity especially for tall buildings. In the maritime industry however, and particularly in the SRtP framework, great focus has to be given to the performance of the ship in casualty scenarios, not only on the protection of the people on board. Indeed, it is essential that minimum life standards are provided in safe areas during an emergency, similarly to protect-in-place scenarios, but also a deep study of systems necessary to make the ship sailing on its own power to a safe port is required. More research on the system perspective is needed.

4

Design Process

In this chapter an overview of the general design process of a vessel is provided in section 4.1, according to the literature available. A focus on the design process for Safe Return to Port projects is given in section 4.3, while in section 4.4 the specific design process for cruise ships at DAMEN CRO is presented.

4.1. General Design Process

The design process of a ship is a complex procedure that brings together a wide range of disciplines. Traditionally, ship design was more art than science, highly dependant on the practical experience of naval architects which were able to explore the multitude of design solutions thanks to a process of trial and error [50]. Even if the modern analysis tools and the new technological challenges altered some of the design procedures, many aspects of the process remained unchanged over the centuries. For example the iterative nature of the design process itself. In fact, it can still be described as a spiral (Figure 4.1), in which all the design steps are repeated in an iterative procedure, in order to approach the final stage: the detailed ship design. The design process of a ship is generally divided in three phases [64]:

- Concept & Preliminary design;
- Contract design;
- Detail design.

The purposes of each of these stages are quite distinct. Every design phase is different in terms of what is analyzed and the level of detail associated with each design element. In the following paragraph the main features of each stage are described.

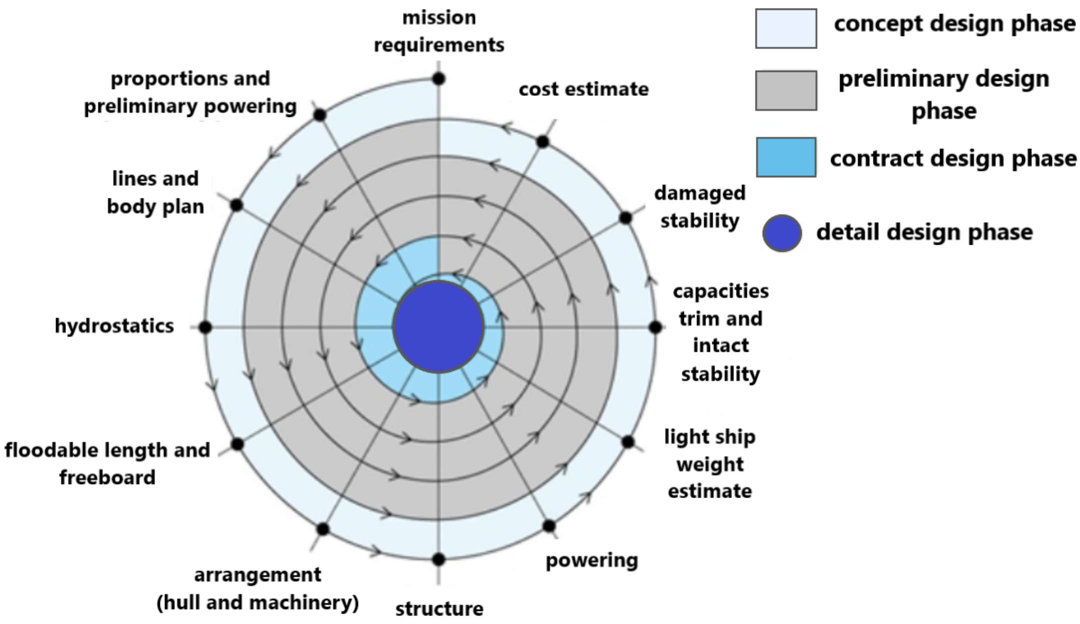

Figure 4.1: Ship Design Spiral, Evans (1959)

4.1.1. Concept & Preliminary Design Phase

For Tupper (2013), this is the most important phase as it establishes the true requirements the designers have to meet. He also believes that it is the most innovative stage, as all the possible different ways in which an owner's requirements can be met must be considered. Papanikolaou (2009) confirms that it is indeed the concept design phase that holds the greatest potential for introducing products and safety innovations. At this stage of the process the routes and the environments in which the ship will operate are determined, the main dimensions are established and the type of hull, the capacity and the speed are decided [64]. As it is clear, some of the most important decisions regarding the vessel are taken in this phase. This allows little possibility to influence cost and performance in all the later design actions, which are inevitably bound within the set frame prescribed by the early decisions [49]. As the design process proceeds, the knowledge about the projects increases while the freedom to make changes decreases, due to the high costs associated with these changes. For this reason a decision-making shift towards the pre-contract stage is required in order to enhance the competitiveness. In Figure 4.2 this shift is depicted. It can be noticed that as the time proceeds, the knowledge about the ship (e.g. the requirements of the clients) increases while the freedom to make changes decreases due to the rise of the costs. It is understood that all the main element of ship design determined during the concept design phase are subject to compliance with the specifications of various national and international maritime rules and regulations [50]. For this reason the designers will have to pay great attention to regulatory requirements. The Concept design phase can be subdivided in [1]:

- Concept exploration - in which a wide range of options are studied. This stage may lead to a small number of different options to be further investigated.

- Concept study - where the options deriving from the concept exploration are analysed in order to find a preferred solution.
- Concept design - which leads to decisions to commit the more substantial effort needed for the later design stages.

In the description of the the sub-steps reported above, it is possible to understand the rationale that designers should follow in order to achieve the most optimal outcome possible.

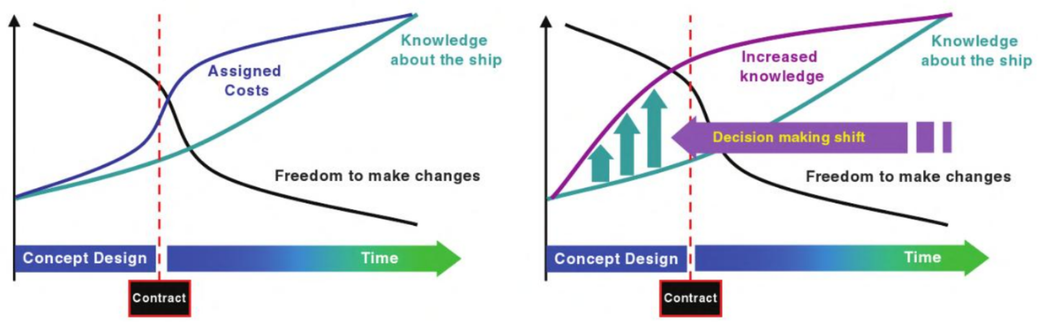

Figure 4.2: Decision-making shift in ship design (Papanikolaou, (2009))

4.1.2. Contract Design Phase

In this phase the design of the ship has to reach a sufficient level of detail to allow the contract to be negotiated between the shipowner and the appointed shipyard. This means that the goal of this phase is the completion of the naval architectural drawings, the exact estimation of the powering, a more precise estimation of the weight of the ship and all the necessary calculations that are indispensable for the formal shipbuilding contract. These calculations will be often carried out by means of software tools like CFD or FEA. The layouts of the various spaces will be produced in enough detail to confirm that adequate space has been allocated in the previous design stages. Not everything envisaged in the concept design will work out as planned, and discussions between the designer and owner will be an ongoing process [64].

4.1.3. Detail Design Phase

This is the last phase of the ship design process. The detail design stage has the goal of providing all the information needed by the production department in order to build the ship. A detailed design of all structural elements of the ship is conducted, along with the setup of the technical specifications for ship's construction and the fitting of equipment. The production units and to the external suppliers have to receive all the information necessary to order equipment and material, according to an agreed build program. Also the specification of tests to be carried out as fabrication proceeds is to be provided [64]. A characteristic of this phase, according to Papanikolaou (2014) is that, while the generated drawings and specifications are the outcome of studies and work of expert engineers (naval architects and marine engineers), the subsequent implementation of the designs into practice depends solely on the capabilities of the shipyard's production units, in terms of both hardware infrastructure and human resources.

4.2. Risk in the design process

From a design company's perspective, a risk in the design process is commonly defined as a mistake or an unforeseen event that has negative consequences on the performance of the company [1]. In other words, a risk in the design is whatever might cause delays or additional costs to the process. A clear example is a design that does not comply with the regulations. Since eventually all the design solutions must be proven to be compliant, alterations to the design will be necessary in later stages of the process where, as explained in the previous paragraphs, every modification is associated to high costs. For this reason, it is essential that every hazard in the design phase is identified and mitigated as early as possible in the process. By doing this, the likelihood of delays or additional expenses will be significantly reduced and the overall performance of the company will be improved. In addition to regulations, also the uncertainty of the requirements can be a source of risks during the design process [40]. If the requirements change during the process, either because the client's changes partially his mind or because the increased knowledge of the project (see Figure 4.2) gives a better understanding on the feasibility of certain requirements, it would eventually result in the need to re-design the project in later stages, with the inevitable negative consequences above mentioned. The time pressure can also be considered as a source of risks. In the design process the time is tight and all the decisions have to be made as quickly as possible in order to enhance the performance of the company. Under time pressure however, designers can more easily mistake or miss some important detail in the design affecting the later design phases.

4.3. Design Process for SRtP Projects

As it has already been said in Chapter 3, Safe Return to Port regulations pose a real challenge to the designers due to the complexity that is now necessary to meet the safety standards. This complexity necessitates a great coordination between the various technical disciplines, working teams and suppliers during the whole design and construction process. The design phase of SRtP vessels is often referred as a "multi-disciplinary" work process [9], because every party involved in the design procedure must observe and apply the same design philosophy and the same design intents (these two notions will be further explained in the following paragraphs). One of the main challenges in the design of a ship compliant with SRtP, according to the "Class Guidelines for Safe Return to Port Projects" by DNV

[1] Source: engineers in DAMEN CRO

GL, is to ensure that all piping, power supplies and controls, including necessary cabling, is done correctly in accordance with the redundancy intent. For example, all equipment and cables related to one of the redundant systems must be routed through compartments that after an eventual casualty does not affect the other redundant system. This care has to be taken for every redundant system considered "essential". Due to the large complexity of the design of SRtP vessels, it is advisable having awareness of these criticalities since the very beginning of the design process. In the following paragraph the main features of the design procedure for a ship compliant with Safe Return to Port regulations are described.

4.3.1. Early phase activities

Since the design of a SRtP ship depends on the capability requirements of Safe Return to Port, which depend on the operational characteristics of the vessel, the first step in the design process is to define the intended operational profile of the ship. This includes the number of passenger and crew, the routes of the ship and the environments in which the vessel is to operate. For example, if a cruise ship is intended to sail in the Pacific Ocean, it is expected a SRtP range of approximately 1450 nm or, if the designated operational theatre is the Atlantic Ocean, 1000 nm is deemed sufficient [9]. Clearly, the operational profile of the vessel affects the capabilities required by the regulations, therefore it is important to properly define it at the beginning of the design process. The next step in the process is to define the ship design philosophy which includes but is not limited to [9] [67]:

- the intended way of designing and arranging the systems affected by the SRtP regulations;
- the redundancy intent;
- the intended level of performance/capabilities (definition of "remain operational" for the essential systems);
- the intended level of manual actions to restore capabilities and remain operational.

Regarding the level of performance required for a system to remain operational, SOLAS does not specify it, neither it is specified in the different circulars. Therefore, for each of the essential systems, the intended level of performance must be defined and specified early in the project. Moreover, also particular requirements of the shipowner should be identified as early as possible in the design process. For example, there could be additional requirements regarding the habitability of the Safe Areas after a casualty or others regarding the operability of the vessel during SRtP operations like manoeuvrability, speed or return capabilities with particular weather conditions.

4.3.2. Ship's description

The ship's description follows from the information gathered during the early phase activities. Once the main design criteria have been established, it is important to organise all the information and to collect all the documents in order to facilitate the coordination of the different parties involved in the complex "multi-disciplinary" work process. As per MSC.1/Circ.1369 [32], the Ship's Description should at least include :

- The design criteria of each individual essential system or group of essential systems to achieve compliance;
- The intended speed during SRtP operations (considering weather and sea conditions) and maximum distance for safe return to port;
- The basic layout of the ship, description of watertight boundaries, A-class fire boundaries, tank arrangement, fire category of spaces;
- The intended locations of the Safe Areas and the criteria adopted for the selection;
- The arrangement, the connections and the description of the power supply of the essential system.

Regarding the criteria for the design of the essential systems, the guidelines mention four options, which may also be combined together. These design criteria are [68]:

- **Separation**: locate components of the system in different A-class spaces or watertight compartments;
- **Duplication**: replace an equipment with two having a smaller size (both necessary for the full service);
- **Redundancy**: install more than one component that is individually able to fully perform the service;
- **Protection**: arrange adequate shields to protect the system (or any of its components) against fire/flooding.

4.3.3. Assessment of required ship systems' capabilities

The following step is an overall assessment of the essential systems. The goal of this assessment is to evaluate if among the essential systems there are *critical systems*, i.e essential systems that could fail to operate adequately in case of a casualty below the threshold. In order to do this assessment it is necessary to investigate ship systems' capabilities after casualty with a systematic approach that should well document the remaining functions of all essential systems. Three different parts of the assessment should be carried out, one for each scenario defined in the Safe Return to Port framework (see Section 3.1). The assessment should follow the process graphically described in Figure 4.3. If an essential system turns out to be fully redundant with respect to all casualty cases below the thresholds, it will be not considered critical, and no further analysis has to be performed. However, if a critical system is found, a relevant detailed assessment is required. This assessment process can therefore be divided in two steps: a first overall evaluation of all the essential systems, and a second detailed assessment of the critical systems identified in the first step [36]. These two stages will be further explained in the following paragraphs.

4.3.4. Overall assessment of essential systems

The overall assessment of all essential systems' capabilities after casualty may be performed in qualitative terms [32]. Essential systems resulted to be fully redundant for all cases of fire and flooding casualties, i.e. if the systems are completely independent with duplicated and separated run of cables, pipes and equipment, do not need to be analyzed deeper and can be considered compliant. Equipment arrangements should be made following the interpretations contained in the explanatory notes and, in the case alternative solutions are preferred, a detailed assessment of those systems should be carried out. The result of the overall assessment of essential systems should be identifying critical systems. If critical systems are found, a second, more detailed analysis of these must be carried out. It is important to highlight that if manual actions are necessary to restore an essential system's functionality, that system must be considered critical.

4.3.5. Detailed assessment of critical systems

When a critical system is identified as a result of the overall assessment, a deeper analysis should be carried out, and the following additional documentation regarding critical systems must be provided (according to MSC.1/Circ.1369):

- details of pipes, cables and other devices connecting the components of the critical system, or connecting different critical systems, including their location within the affected area;
- details of any manual action providing the required system's functionality;
- details of any operational solution forming part of the design criteria;

A quantitative analysis may be carried out, where accepted by the Administration. Some techniques are suggested in the explanatory notes [32]:

- quantitative analysis of fire risk within a space, supplemented by fire engineering analysis and fire testing, when necessary;
- Failure Mode an Effect Analysis (FMEA) of a system or component, in accordance with standard IEC 60812 "Analysis techniques for system reliability-Procedure for Failure Mode and Effect Analysis"; or resolution MSC. 36(63), annex 4, "Procedure for Failure Mode and Effect Analysis.";
- detailed analysis of possibility of flooding of internal watertight compartments and of consequences of flooding on system components, given the location of the compartment and arrangement of piping within the compartment.

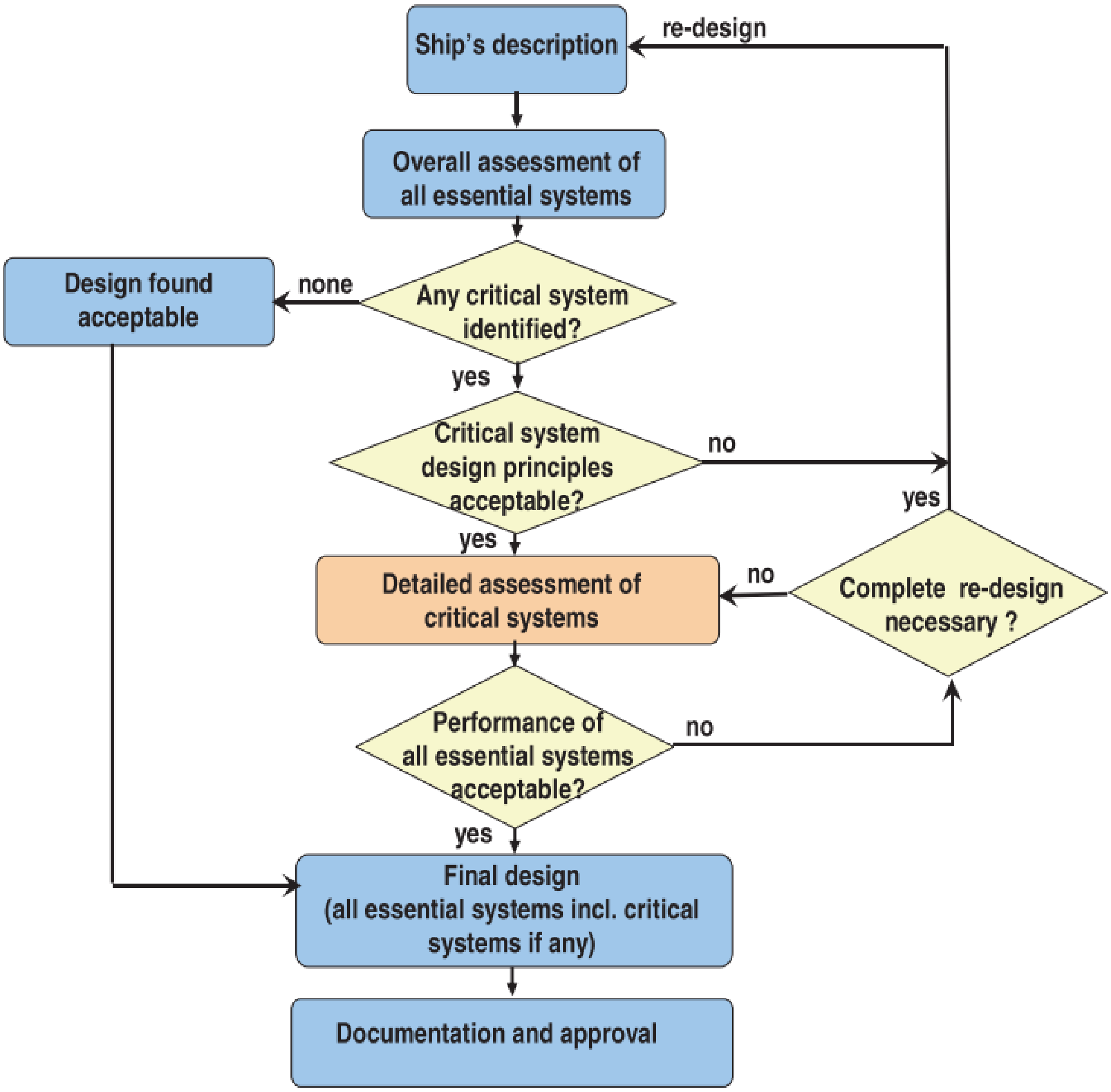

Figure 4.3: Assessment process flowchart as shown in appendix 2 of MSC.1/Circ.1369

4.3.6. Final approval and documentation to be kept on board

When the assessment of all essential systems' capability to fulfill SRtP requirement has been successfully completed, the assessment report together with the ship's description file can be submitted to the Administration or to the Classification Society acting on its behalf for approval. Such approval will be valid taking into account the intended area of operation and operating pattern as defined in the ship's description. During the vessel's life, any changes in the ship's design or in the way the vessel will be operated, will have to be evaluated with respect to compliance with SRtP requirements. Therefore documentation as listed in MSC.1/Circ.1369 paragraph 7.4 will have to be kept on board and up-dated when necessary. This documentation shall include the ship's file and the assessment report, together with required operational information related to operation of essential systems and availability of safe areas, and description of tests, inspection and maintenance plan related to the concerned essential systems.

4.4. DAMEN's Design Process

The following description of DAMEN's design process for cruise ships resulted from several interviews with the engineers [2] of the D&P (Design and Proposal) office at DAMEN CRO. The first relevant difference between the design process at the company and the one described by the literature available on the topic, is the distinction between "Design phase" and "Engineering phase". The first one is considered to include all the steps that lead to the signature of the contract, while the "Engineering phase" takes over once the contract has been signed. To link this subdivision of the Company's design process to the one available in the literature (see Section 4.1), the Concept design phase and the Contract design phase can be included in DAMEN's "Design phase", while the Detailed design stage corresponds to DAMEN's "Engineering phase". This distinction is motivated by the intrinsic difference between these two concepts and terminologies. While "designing" requires dynamism and creativity to meet the uncertain requirements of the client, the engineering part mainly consists of calculations and less effort is made to follow the variable requirements of the costumer, which should be more fixed at the point the contract is signed. It is clear from Section 4.1 that most of the crucial decisions regarding ships' design are carried out in the first stages of the design process, especially in the Concept design phase. For this reason, DAMEN CRO gives great attention to the "Design phase". A detailed description of this stage is provided in the following paragraphs.

[2]Deniz de Koningh, Tender Manager DAMEN CRO
Aleksander Markovich, D&P Engineer DAMEN CRO
Luca Codiglia, D&P Engineer DAMEN CRO
Lennaert de Haan, Lead Engineer DAMEN CRO

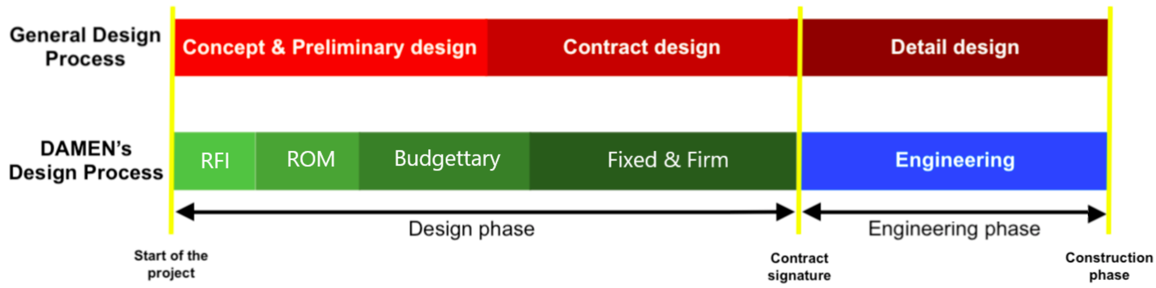

Figure 4.4: General design process and DAMEN's design process – Timeline comparison

4.4.1. DAMEN's Design phase

This design phase is usually further subdivided into four steps (considering the RFI phase). It is important to say that the design process does not always follow this procedure, in fact it might happen that some of the first steps are carried out by the shipowner or by a specific design company (or design bureau) on his behalf. In any case, the design phase begins with the Request For Information (RFI), when the client approaches a large number of shipyards (up to 20), to learn more about the organisation, competence and experience of the shipyard in the construction of the type of vessel he is interested in. During this phase, the shipyards collect the information to be provided to the client. Once the shipowner has assessed the different shipyards, he drafts the so-called Longlist, namely the list of the shipyards judged to be capable to carry out the project (more or less 10 companies). To the companies in the Longlist, the client gives conceptual drawings of the ship to be built, executed by the shipowner or by an external company hired for this purpose. In the cruise industry, it is often the case that these drawings provide mainly information about the aesthetics of the ship and the "hotel" areas, generally neglecting the lower decks, i.e. the technical areas. Once the shipyard has received the drawings from the client, the actual design process of the company begins. In every stage of DAMEN's "Design phase", the design process follows the typical iterative process known as Design Spiral, previously mentioned in Section 4.1. The specific design spiral used in DAMEN CRO for cruise ships is depicted in Figure 4.5. At every stage different iterations are performed, every time going more in detail with the design. The design decisions regarding Safe Return to Port requirements carried out during the design process are summed up in Table 4.2. In the following paragraphs, a description of each stage of the "Design phase" is provided.

Rough Order of Magnitude (ROM)

After the shipyard received the client's drafts of the ship, the design team has to collect all the information necessary to make an offer with a 10% of margin called ROM (Rough Order of Magnitude). This procedure usually lasts from two to four weeks. In this phase the shipyard does not have the "design responsibility", i.e. it is not responsible for mistakes in the design. The reason is that both the functional requirements of the ship as well as the technical solutions to meet the requirements are provided by the client. The task of the design

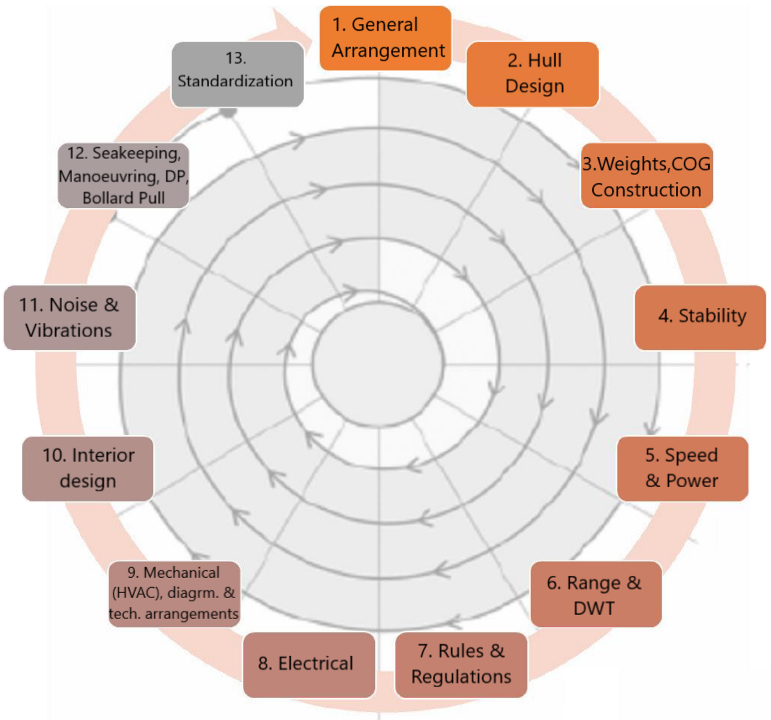

Figure 4.5: The Design Spiral for cruise ships – DAMEN CRO (de Koningh 2019)

team of the shipyard is to analyze the information received and to do quick calculations in order to prepare a ROM as accurate as possible. This is performed by "screening" the drawings provided by the shipowner in order to estimate the main drivers of the ship's cost like dimensions, power and other major features. Even if the shipyard is not responsible for the risks in the design (as defined in Section 4.2), it is common sense to start considering the possible hazards already at his stage. In fact, the following stages would highly benefit from the increased awareness about the risks in the design. If criticalities are found, they can be reported to the client, who might review his drawings for the ROM. Once the shipowner received the quotations of the shipyards in the Longlist, few companies are selected, and they are now part of the Shortlist (4-5 shipyards).

Budgettary

Unlike the ROM phase, in the Budgettary phase the shipyard has the responsibility of the design. In fact, instead of the technical solutions, the client now provides the functional requirements of the ship. It is the shipyard's task to come up with the design solutions to meet the requirements. In this phase, which usually lasts for 2-3 months, the design process follows the cyclical procedure described in Paragraph 4.1. Two to three iterations are carried out during this phase. Among the most important design decisions carried out at this stage there are:

- GA (General Arrangement), compartmentation and spaces allocation;
- Linesplan;

- Preliminary stability calculations;
- Preliminary weight calculations and COG (Centre Of Gravity);
- Power, speed and initial sailing profile;
- Global tank layout;
- Preliminary interior space design.

A complete list of the design activities to be performed in the Budgettary phase can be found in Table 4.1. During the Budgettary phase it is imperative to mitigate all the possible risks in the design process. In other words, it is essential to consider and apply the major requirements of the regulations. The level of implementation of the safety requirements must follow the level of detail of the design. In the first iteration of the Budgettary phase for example, it important to verify that the compartmentation is in line with the redundancy level required by SRtP rules (e.g. double engine room, separated switchboards, double propulsion, etc.). While the process proceeds and the design reaches a greater level of detail, the designers must keep the regulations in mind, in order to implement every requirement when it is convenient (i.e. as soon as possible). After the last iteration of the Budgettary phase has been performed, the design company makes an offer with a 5% margin: the Budgetary Offer. At this point the Request For Proposal ends and the last stage of DAMEN's "Design phase" begins.

Fixed & Firm (F&F)

If the Budgetary Offer of the shipyard has been accepted, it comes to the Fixed & Firm phase. Even if the contract is not signed nor formulated yet, the shipyard at this stage is the only party involved in the construction of the ship. The Letter Of Intent is a formal document of mutual agreement where the shipyard commits to design and build the vessel. During this phase (usually 4-5 months), further iterations in the design spiral are performed and the design reaches the sufficient level of detail to allow an accurate formulation of the formal shipbuilding contract. The main design activities in this phase are:

- Contractual GA plan;
- Space type & categorisation plan;
- Hullform hydrodynamic optimization;
- High level section plan;
- Intact & damage stability report;
- Multiple loadcases power & speed;
- Detailed tank arrangement;
- Conceptual routing of main cable runs;
- Main system & components placement;
- Detailed interior design studies.

Every design activity carried out at this stage is reported in Table 4.1. Similarly to the Budgettary phase, also during the Fixed & Firm phase the regulatory requirements must be taken in account throughout the spiral process with the correct level of detail. In relation to Safe return to Port rules, also the first concepts of the Failure Mode and Effect Analysis are performed at these stage. At the end of this phase, the Fixed & Firm offer (F&F) is made and, if accepted by the client, the contract is signed and the "Engineering Phase" begins.

RFI	ROM	Budgettary	Fixed&Firm	Engineering Phase
• Collecting the information on the project (Does it have to comply with SRtP reg.?) • Definition operational pattern	• Screening client's GA • Compartmentation according to redundancy requirements • Allocation spaces required	• Area quantities in GA according to redundancy requirements • Initial evacuation plan • Power & speed calculations (SRtP loadcases) • Initial main systems diagrams & components placement • Space reservation routing of main systems	• Active/passive fire fighting plan • Detailed power & speed calculations (SRtP loadcases) • Main systems diagrams & components placement • Conceptual routing main ducts • Initial SRtP failure mode study	• Detailed routing and piping of systems • Detailed SRtP failure mode study

Table 4.2: Design decisions regarding SRtP regulations in the different deign stages

4.4.2. DAMEN's Engineering Phase

During the "Engineering phase" the design coming from the LOI is further developed. At this stage the design has to reach the level of detail required for the construction plans, in order to provide all the necessary information to build the ship to the production units. Even if all the main decisions regarding different design solutions have already been carried out in previous stages of the process, there is still the need to consider the safety requirements. For example, the detailed drawings of the systems on board are executed in this phase and it is essential to keep in mind and the goals of SRtP rules in order to implement the redundancy intents required by the regulations. This is particularly important for the detailed piping plan and for the routing of the systems. A clear understanding of the objectives of SRtP regulations is mandatory during the whole "Engineering phase". Another important feature about this phase is the necessity of demonstrating the compliance to the different national and international regulations. Once the contract has been signed, the Flag state is officially assigned and additional regulatory constraints must be followed and verified. In connection to Safe return to Port, the assessment of the essential system has to be performed once the layout of is defined in detail (see Paragraph 4.3.4). Another important task in this phase is the preparation of the documentation to be provided to the Classification Societies (CS) for approval. More specifically, all the assessment reports have to be collected, together with the maintenance plan of the essential systems.

4.5. Third party design company

Instead of doing the whole design of the ship "in-house", DAMEN may outsource it to a third party design company specialized in the sector [24]. For complex SRtP project for

	ROM (1-2 weeks)	Budgettary (4-6 weeks)	Fixed & Firm (4-6 months)
General arrangement	List of spaces including area requirement Quick analysis of main logistic and people flow Basic evacuation flows and escape route check Remark/suggestion on client GA	GA plan with validate area quantities Initial evacuation plan(incl. LSA positioning) Main Vertical Zones placement Initial fire integrity check Initial hazardous zone check Visualized flow of passengers, food, garbage Lifeboat placement ; Set MVZ's	Contractual GA plan Space type plan Active/passive fire fighting plan Space categorisation plan Fire integrity plan Hazardous/EX zone plan
Hull design	Principle dimensions Form coefficients	Sectional area and waterline characteristics Linesplan	Hullform hydrod. optimization (CFD) Hull appendages
Weight, COG, Construction	Rough weight and COG check (based on factors) Basic Mainframe (reference ship)	Weight and COG calc. incl. breakdown on main weight groups Determine margins Mainframe design including principle detail designs (eg girder, pillars) Longitudinal strength analysis	Initial NAPA construction weight study Weight and COG calculation including breakdown on system level Buckling analysis High level section plan
Stability	Initial intact stability check (based on client input) Floating position of the ship	Intact and damage stability study Bulkhead positioning / MVZ	Intact and damage stability report
Speed & Power	Quick power & speed check based on client input (PSD diagram)	Power speed calculation (multiple loadcases, incl. SRtP, prop. design) Initial sailing profile and propulsion config. study (propulsion battery capacity, etc) High level demarcation check with suppliers and yard (engine, prop.)	Power speed calculation (multiple loadcases, incl. SRtP) Detailed sailing profile and prop. config. study (propulsion, battery capacity, etc.) Detailed demarcation handshake between suppliers and yard (engine, propulsion)
Range, DWT, Tanks	Initial range calc. based on client input (tanks, provision)	Global tank layout DWT distribution Range calculation	Detailed tank arrangement Range calc. update Deadweight composition for spec
Rules & Regulations	Initial SRtP screening of GA Initial SOLAS 2020 screening of GA Cross check remaining rules & reg.	Initial compliance matrix Rules & Regulation Initial GP-FB-EN-GT-NT calculation Alternative design topics overview SRtP approach	Detailed compliance with matrix Rules&Reg Exemptions list Alternative design discussed and covered Passenger evacuation flow analysis Safe Return to Port failure mode study GP-FB-EN-GT-NT calculation
Electrical, Automation, AV/IT	Preliminary hotel load verification (factors reference ship)	Estimated load balance Initial single line diagrams (propulsion, ship service power, hotel) High level demarcation check with suppliers and yard (electrical, automation, Nav/Naut and AV/IT) Space reservations main E&A equipment	Load balance Single line diagrams main networks Detailed demarcation handshake supp.&yard (electrical, automation, Nav/Naut and AV/IT) Space reservations MVZ's(GA, tech. arrang.) Conceptual routing of main cable runs Identify EMC/EMI zones
Mechanical (HVAC), diagram and technical arrangements		High level demarcation check with suppliers and yard (HVAC, stabilizers& other systems) Initial main system diagrams and including component placement (input SRtP) Space reservation HVAC auxiliary systems, piping and equipment Initial space reservation for routing main ducts (GA and mainframe)	Detailed demarcation handshake supp.&yard (HVAC, stabilizers & other significant syst.) System diagrams main syst. and components placement(fuel,stored energy, LNG storage HVAC,Hydraulics, fresh/tech/sewage water) Basic technical arrangements Conceptual routing of main ducts Heat balance
Interior design	Example interior design renders Determine level of interior required (reference ship)	High level demarcation check with suppliers and yard Initial interior design studies incl. renders Preliminary weight budgets	Detailed demarcation handshake between suppliers and yard Detailed int. design studies incl. 3D renders Agreed weight budgets
Noise & vibrations	Preliminary check of noise and vibrations requirements	Asses sound requirements and define sound& vibration risk areas on GA Initial noise isolation space reservation on GA/mainframe in prob. areas Vibration natural frequency check	Detailed noise study, floating floor and cavity design Natural frequency/plate vibr. analysis Frequency response analysis
Seakeeping, DP manoeuvring		If any strict class/owner requirements, one of these studies to be performed Seakeeping and Crabbing analysis	If any strict class/owner requirements, one of these studies to be performed Funnel smoke analysis
Standardization	Select&process re-usable documents and calc. sheets for future use	Select & process re-usable documents calculation sheets for future use	Select & process re-usable documents calculation sheets for future use

Table 4.1: DAMEN's Design phase - Design stages and activities for cruise ships

example, the whole Design Phase is often outsourced to KNUD E. HANSEN, a danish company that provides design and engineering services for customized vessels. When a third party design company is employed to carry out the first part of the design, the task of the engineers of the D&P office at DAMEN CRO is to double check the drawings provided by the design company, making sure that the requirements of both regulations and client are met before handing the project in to the Engineering phase.

4.6. Uncertainty of the requirements

The uncertainty in the client's requirements is another challenge in the design process. If it is deemed difficult to find the right technical solution to meet a certain requirement, it is indeed more complicated when the requirement is not fixed or well defined. The level of uncertainty at the beginning of the project is different from sector to sector. In the cruise industry for example, the level of uncertainty of the client's requirements is much greater than in the offshore industry. In the offshore sector in fact, the high competitiveness of the business results in the need of having all the knowledge to build the vessel "in-house", and there usually are clear ideas on how the vessel should or should not perform. For this reason, the shipyards often receive detailed drawings of the project from the costumer, including all the technical solutions employed. For the cruise industry however, the shipowner has often only a concept of the hotel and entertainment areas of the ship, leaving to the shipyard the burden of designing the technical decks. The level of uncertainty of the requirements changes also during the design process of the project. While the design is being developed, the requirements get more and more defined. This trend is depicted in Figure 4.6. The X coordinate represents the uncertainty of the requirements while in the y axis the uncertainty in the technical specifics is represented. As it can bee seen, the uncertainty is maximum at the beginning of the project and it decreases at every stage of the design process, it reaches zero only when the ship is delivered to the client. The variability in the requirements creates additional risks in the design phase and it must always be considered by the designers.

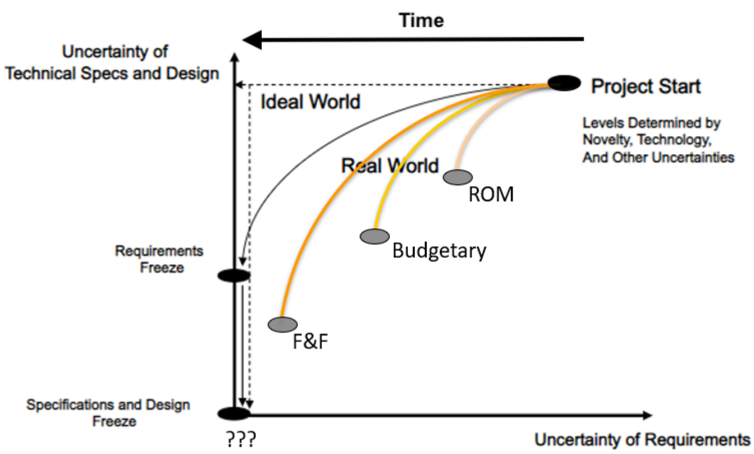

Figure 4.6: Uncertainty of requirements and uncertainty of technical specifics in DAMEN's design stages.

5
Problem Definition

5.1. Mitigation of risks in DAMEN's design process

As already defined in Section 4.2, the risks in the design process are mistakes or unforeseen events that cause delays or additional costs to the company. The most common example is a design that turns out to be not compliant with the regulations, so to require alterations in later stages, with obvious negative consequences in terms of costs and delays. Indeed, Safe Return to Port rules represent a significant source of risks for the design companies, due to the complexity of the solutions required and especially to the difficulty in verifying the compliance of the designs. DAMEN CRO, as design company with focus on small to medium passenger ships, is obviously largely affected by these risks. Therefore, one of the main priorities during the whole design process is trying to mitigate all the risks involved in the process as much as possible. The mitigation of the risks entailed by the regulations is usually performed at every stage of the process:

- In **ROM**, it is essential to screen the GA provided by the client trying to quantify the risk of the project. If the vessel has to be SRtP compliant, the designers check that all major requirements have not been neglected (e.g. two separate switchboard rooms or the absence of escape spaces). By identifying these problems already at this stage, the likelihood of building up the project on the client's mistakes is significantly reduced.

- In **Budgettary** and **Fixed & Firm**, if the design of the ship is carried out by the company, it is necessary to verify the compliance with the rules after every design decision made. This is especially true for the complex design process of SRtP projects. Since, as defined in Section 4.3, it consists of a multi-disciplinary work, different design teams of specialists make diverse decisions about the design and the loss of focus on the goal of the requirements is not very unlikely. It is therefore fundamental to evaluate the compliance of the design after every iteration in the design spiral in order to reduce the risks in the process.

- If the design phase is outsourced to a third party company as described in Paragraph 4.5, the evaluation of the design is still essential due to the large possibility of mistakes in the design. For this reason, the D&P office at DAMEN CRO, assesses the compliance of the design with the regulations before handing the drawings in to the Engineering department.

From the above analysis on the methodologies to reduce risks in DAMEN CRO, it results that the mitigation of the hazards entailed by the regulations in the design is mainly performed by means of a thorough analysis of the design at every stage of the process.

5.2. Design evaluation to mitigate risks

It can be understood from the above paragraph that a perfect evaluation can eliminate the risks in the design process that regulations like Safe Return to Port entail. However, this is true only in the ideal world. In practice, the analysis can rarely be performed in a optimal way. There are several reasons why the actual assessment differs from the ideal one. First, it is important to mention that the assessment of the designs is an extremely complex task for which many aspects and factors have to be taken into account. Experienced engineers are fundamental to achieve this goal, but it is not always enough. The design of a ship compliant with the SRtP involves a simultaneous evaluation of the ship functional capabilities requested by SOLAS, the redundancy of the systems components, their level of segregation and the great interdependence of systems and subsystems makes the assessment of the design a problematic task even for the most skilled designer. Thus, it should not surprise that Cangelosi et al. (2018) claim that this goal can only be successfully pursued with the aid of specific software tools. To efficiently mitigate the risks of the regulations, i.e. to efficiently assess the compliance of the designs, a structured methodology, a good knowledge of the problems entailed by the regulations and an effective tool able to support the designers in this complex task are essential. A tool to support designers in the assessment of the design is not only necessary due to the complexity of the task. Indeed the limited timespan in which the designers can mitigate risks also requires the aid of a tool. As mentioned in Paragraph 4.2 also the time pressure is considered a potential source of risks in the design process. In this connection, a tool could speed up the evaluation process and reduce the possibility of mistakes in the assessment made by the designers.

5.3. Existing support tools for ship designers in SRtP projects

Even if support tools are deemed necessary to help designers throughout the whole complex process of designing ships compliant with Safe Return to Port [68], there are few software products or models available in the market or in literature for this purpose. A reason after this is that all the main shipyards and design companies who deal with these complex projects develop their own support tools in-house. Due to the large competitiveness of the cruise industry indeed, there is no interest in sharing this knowledge outside the company. It is known for example that Fincantieri, one of the largest shipbuilders in the world, is developing dedicated researches for supporting the process of ship design and approval [6]. In this respect, Romano et al. (2010) mention a decision support tool developed jointly with the University of Udine, meant to help engineers during the design of cruise ships, referred by the authors as one of the most complex environment for decision making.

In addition to shipyards and design companies, also some software firms developed products to support designers in their work. A significant part of the software available in the market concerns the stability studies of the ship. Products like PROTEUS3 [55], FREDYN [70], NAPA [43], PIAS [56], simulate flooding in the ship and they can therefore be applied to SRtP scenarios. These software tools are usually used to assess the stability of the damaged ship and most of them, e.g. PROTEUS3, can also be used to modify the watertight arrangement of the vessel [66]. Since, as discussed in Chapter 4, the compartmentation of the ship is an important step in the design of SRtP projects, with the aid of these tools this can be performed according to the redundancy intent of the regulations without compromising the stability of the vessel. NAPA and PIAS products can also be used as CAD software from the preliminary sketch to final design but they are not provided with any specific function for SRtP regulations. In addition to the software available in the market, regarding the stability of the vessel, many models have been developed by researchers in order to study the behaviour of a damaged ship in SRtP scenarios. Spanos et al (2011) for example, analysed the survivability of damaged ROPAX vessels. Espinoza Haro et al. (2017) investigated the motion responses and flooding behavior of a damaged passenger ship advancing in waves.

On the market there are also software products for the evaluation of the compliance of the designs with Safe Return to Port regulations, described in the previous sections as a fundamental step in the process of designing passenger ships. Among the most known companies who provide this kind of software there are Brookes Bells [2], Global Maritime [37] and Deltamarin [8]. Even if Paragraph 5.1 concluded that the evaluation of the compliance of the design is the most effective method to mitigate risks in the design process, these software tools cannot be used for this purpose. In fact, the software requires a good level of detail of the design to work, and it cannot be used in the early stages of the design process [1]. Moreover, the amount of time needed to model the design in these tools is considerable (up to 0.5 manyear in the case of Brokes Bells [2]). Also for this reason it is considered illogical applying these software products in the early stages of the design process when even the requirements of the vessel are uncertain (see Figure 4.6). The mitigation of risks however, in order to be efficient, has to be performed in the very first stages of the design process, as described in the above paragraphs. It follows that these software tools to evaluate designs cannot be used for the purpose of this thesis, i.e. the mitigation of the risks in the design

[1] Source: engineers in DAMEN CRO
[2] Source: Broken Bells software engineer

process entailed by SRtP regulations.

5.4. Assessment tool for early design stages

From the analysis of the mitigation of Risks in DAMEN's design process in Paragraph 5.1, it resulted that an accurate assessment of the designs is the best way to mitigate the risks involved in SRtP projects. In paragraph 5.2, with some considerations and the aid of the literature, it has been shown that support tools in the design of SRtP vessel are needed, especially in the evaluation of the compliance with SRtP regulations due to the large complexity of the task. In paragraph 5.3, the support tools available in the market and in literature have been discussed, and a gap in the research has been found. Thus, the result of this section is that a tool able to assess the compliance of the design is necessary to mitigate the risks entailed by Safe Return to Port regulation. However, to efficiently mitigate the risk this evaluation has to be performed since the very beginning of the design process in order to identify the criticalities when they can be conveniently solved, and there are no tools in the market for this purpose. The aim of this thesis project is filling this gap.

5.5. Requirements for tool to mitigate risks in the design phase

Since it has been concluded that a support tool for the assessment of design is the best approach to meet the research goal of this thesis, the requirements of such a tool are now to be delineated. The most important requirement is obviously the **ability of assessing the design**. The assessment should be preferably performed in a qualitative fashion rather than a quantitative one (should be performed in absolute terms). In other words, the tool should assess if a system is reliable enough to be compliant with the regulations in a binary way, and should not evaluate which among different layouts or variants of a system is less or more reliable. Indeed, the result of the evaluation should define whether a design is compliant, and not to assess the overall safety of the design. It follows from the first requirement that the tool must be capable to evaluate complex ship design (meaning several systems with many components each), therefore it must have the **sufficient computational power** to handle the considerable amount of information needed to be elaborated.

Another major requirement is that the tool **must not require a great level of detail** of design to be employed. As already discussed in the previous paragraphs, an effective mitigation of the risks has to be carried out since the very first phases of the design process. At this stage however, the design does not have the necessary level of detail, for example, to be tested with the software products discussed in Paragraph 5.3. A tool able to assess the compliance of the very first design decisions in the process is necessary. In Figure 5.1, the "area" of application of the tool within the design process is depicted, also in relation with the existing tools available in the market. Since the tool has to be utilized in the early stages, it must be able to deal with the uncertainty of the requirements efficiently, e.g. it should not require many manhours to model the design.

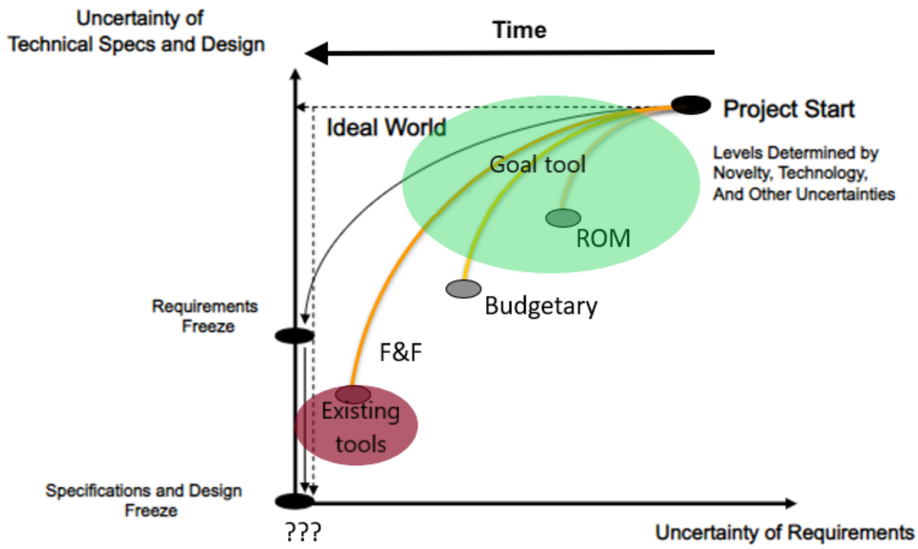

Figure 5.1: Area of application (within the design process) of the goal tool in relation with the area of application of the existing tools available in the market

An additional requirement is the convenience of the tool in terms of **quickness and ease of use**. The assessment of the design is currently executed by hand and, even if as discussed in Paragraph 5.2 a tool for this task is almost fundamental, this would be hardly accepted by the designers if it requires a lot of time and effort to function. Therefore, it is essential that the information coming from the designs can be efficiently implemented in the tool and that the results of the evaluation are promptly displayed. Another important requirement of the tool is that it has to be **reusable**. In other words, the tool cannot be developed *ad hoc* for a project, but it must be flexible enough to be used for different projects and even for different vessels that are to be compliant with SRtP regulations (ideally from a small ro-pax to a mega cruise ship).

Furthermore some additional features might be desirable for such a tool even if not strictly necessary. For example, the tool could give indications on what and where the problems are in case of non compliant design. In other words, it should not work as a "black box" in which the designers implement some information regarding the design as input and the tool provides just a feedback about the compliance as output with no clues of the criticalities, if any. Indeed, knowing which and where the problems of the design are is extremely important for the engineers in order to be able to efficiently solve them. In this connection, the tool could also provide hints to the designers on how to fix the defect found in the design. If, for example, the compliance with SRtP cannot be achieved due to the wrong placement of a redundant component, given the information in input, it could suggest where the component can be placed in order to meet the requirements. Even if the last two requirements would significantly support the designers in the process of designing a vessel, they exceed the objective of the thesis, namely the mitigation of the risks entailed by the SRtP regulations. Therefore the goal of the project can be considered achieved if a tool with all the requirements but the last two is set up. An overview of the requirement is provided in Table 5.1.

	Requirement	Purpose
Essential	• Ability to assess design • Sufficient computational power • Low level of detail • Quick and easy to apply • Reusable	• Verify the compliance of the design • Elaborate significant amount of data • For early stages of the deign process • Convenience of use for the designers • Applicable for different projects
Optional	• Providing insight of possible criticalities • Providing hints for design improvements	• Awareness of the problems of the design • Suggest solutions to achieve compliance

Table 5.1: Overview of the requirements for the Assessment Tool.

6

Possible Solutions

In Chapter 5 it has been concluded that the assessment of the designs is the optimal strategy to mitigate the risks entailed by Safe Return to Port regulations. Since the most problematic aspect of the evaluation of the design is the assessment of the availability of the essential systems after a possible casualties (due to the large complexity of the systems), different methods commonly applied for availability and reliability studies are analysed in this chapter. The scope of Chapter 6 is to identify the best solution to meet the requirements described in Section 5.5, in order to develop an effective tool able to mitigate the risks in the design process.

6.1. Markov Chain approach

Markov Chain is a stochastic model describing a sequence of possible events in which the probability of each event depends only on the state attained in the previous event [18]. Indeed, Markov chain is suited for describing various conditions of a system and the transitions between them over time. For this reason, there are many application of Markov chain in the reliability analysis of diverse type of systems in different industries.

A Markov chain approach has also already been applied in the assessment of the reliability of systems in SRtP framework. Kim et al. (2016) use a Markov chain model to assess the reliability of a low-demand operational mode fire water supply system. The research aimed to compare the reliability of a non-compliant water supply system with one meeting SRtP requirements. Other research in the maritime industry focuses on the availability of systems in damage scenarios, although not in a SRtP context. Habben Jansen et al. 2019 analyse the vulnerability of the propulsion system and the chilled water supply system for an Ocean Patrol Vessel (OPV). Even if this vulnerability study exceeds the scenarios considered by Safe Return to Port regulations, it shows how this method could be implemented to assess the availability of the systems in damaged ship scenarios. Indeed, the philosophy of the research, namely assessing the capability of a system after the loss of one or more compartments, is very similar to the approach required to evaluate the compliance of a system under SRtP rules. A valid feature of the model of Habben Jansen et al. is the representation of the ship as a network. This allows the model to operate in the early stages of the design process, since it only needs information about the position and the connections of the system components. In addition to this, once the network of the ship has been implemented with a marginally laborious work, the model itself could be quickly re-used to test other configurations of the same system or different systems.

Among the weaknesses of a Markov Chain model there is the small computational power of the approach. Brameret et al. (2013) claims that the exponential blow-up of the size of the problem as well as the difficulty in designing the model limit its use even if it is an efficient and versatile tool to calculate reliability indicators of designed systems. In this connection, the model developed by Habben Jansen et al. was limited to a 13 edges network for a normal, modern PC using standards settings MATLAB [22].

6.1.1. Strengths and weaknesses: Markov chain method

Markov chain approach is capable to evaluate the availability of systems in casualty scenarios. As it has been implemented so far however, the evaluation is not qualitative, i.e. it cannot assess whether a design is compliant with the regulations or not. It can be applied in early stages of the design since it does not necessarily require a great level of detail but it has limited computational power. The concept of a network as representation of the ship (see Habben Jansen et al. 2019) is quite intuitive and it is reusable to some extent even if it might require some effort to model.

Strengths	Weaknesses
• Able to assess availability of systems	• Does not verify compliance
• Low level of detail possible	• Low computational power
• Can be applied to network model	• Needs some time to model
• Overview of distribution of system in network	

Table 6.1: Strengths and weaknesses Markov Chain method

6.2. Fault Tree Analysis and Location Fault Tree

Fault Tree Analysis (FTA) is the most commonly used technique for causal analysis in risk and reliability studies [53]. It consists of a top-down approach to failure analysis, used to identify all possible combinations of basic events that may result in a critical event called the "TOP event". The causes of the "TOP event" are identified and connected through logic gates and the process goes on until the desired level of detail is reached.

Fault Tree Analysis is easy to implement and gives the designers a clear overview of what is analysed. Indeed, the system is broken down step by step and it allows to better understand the causes of a failure, simplifying the redesign process if needed. FTA studies can be either qualitative or quantitative, given the failure rates of the basic events [69]. For these reasons, FTA is commonly applied to assess the reliability of systems in diverse industry. Kim et al. [34] use a revised version of the Fault Tree Analysis, the Location Fault Tree (LFT), to assess the reliability of a fuel oil system in a continuous mode of operation under SRtP regulations. LFT is a fault tree whose basic events are sabotage-induced damages on the locations where various safety-related components are located, and it is often used for vital area identification of nuclear power plants [20]. Since for LFT the causes of a system failure are not random hardware failures but external causes, and the basic event of LFT is the loss of a room, it has a lot in common with the features of the SRtP regulation [34]. Instead of sabotage for the study of nuclear power plants, in SRtP scenarios the basic events are caused by flooding or fire casualties.

Even if FTA and LFT are efficient methodologies for the assessment of the reliability of systems, largely applied in almost every industry, they also encompass shortcomings. Above all, for complex systems, the diagrams of these assessment techniques become enormous, and they are therefore extremely time consuming to set up and very complicated to follow [17].

6.2.1. Strenghts and weaknesses: FTA & LFT

Both these approaches are able to assess the availability of the system and it is possible to evaluate the compliance with the rules since, as Kim et al. state in the evaluation of the fuel systems, it is immediately possible to notice the physical separation of the system SRtP compliant. Moreover, they are suitable for every stage of the design process since the level of detail is flexible and it is decided by the designer with the selection of the "basic events". Fault Trees could potentially assess complex systems since they are not limited by computational power even if the diagrams of large systems become very complicated and therefore particularly time-consuming to implement. Furthermore, these approaches give a nice overview of the potential criticalities of the system but they are not reusable for different systems or different layouts of the same system, since dependant on the location of the components.

Strengths	**Weaknesses**
• Able to assess compliance of systems	• Difficult to implement for large systems
• Flexible level of detail	• Not reusable
• Potentially limitless computational power	
• Neat overview of criticalities	

Table 6.2: Strengths and weaknesses FTA & LFT

6.3. Functional chain analysis

As for the case of Markov chain approach, many approaches used to assess the vulnerability of navy vessel can be applied in the evaluation of the compliance of cruise ship designs with SRtP regulations, thanks to their many similarities. In this paragraph, the method to assess the vulnerability of ships in the naval department of the DAMEN group (DAMEN SCHELDE) is described [1].

The process begins with the decision of the desired level of survivability for the vessel in different casualty scenarios. For light damages it may be required to be able to fight while for more severe damage scenarios the function "float" might be sufficient. In addition to the residual capabilities, also the entity of the threats and the weapon effects are identified. Once the functionalities have been determined, the systems necessary to grant them are selected. Next to the main systems, on a higher level of detail, also the auxiliary systems and the subsystems required to the main systems to function are identified.

The components of the systems are then depicted in a block diagram, in order to have a neat overview of the many elements to be analysed. The redundant components are illustrated in parallel blocks while the non-redundant ones in series. This process, named Functional Chain Analysis (FCA), is mainly meant to better visualize the interdependence of the systems and their components in a navy vessel. These diagrams are then utilised to support the engineers in the evaluation of the vulnerability that is performed "by hand" considering at every step a compartment lost. Even if the actual assessment is performed "manually" by the vulnerability engineer, the FCA diagrams are fundamental to provide an overview of the many elements to be considered dealing with complex systems. These diagrams can also be used to suggest the rationale during the design phase of the systems, with the aim of reducing the vulnerability of the vessel. In this connection, parallel components (i.e. redundant components) will be preferably placed as far as possible from each other while in series components will be preferably placed in the same compartment or nearby it.

6.3.1. Strength and weaknesses: Functional chain analysis

With the methodology used in DAMEN SCHELDE is possible to assess the compliance of a system with SRtP regulations and it would not ideally be limited by the computational power. It is suitable for low detail design stages and, for similar systems, it can also be somewhat reusable. Unlike FCA and LFT that are dependent on the location of the components in the ship, the FCA diagrams are merely based on the structure of the systems, and for this reason they could be reused for similar systems. An additional advantage of this

[1] The method to assess the vulnerability of navy vessels built in DAMEN has been discussed during a meeting at DAMEN SCHELDE in Vlissingen on February the 2nd with **Sander Allefs** (Technical Specialist Ship Vulnerability and Signatures) and **Joep Broekhuijsen** (Project Manager Research Coordinator)

approach is the design rationale provided by the FCA diagrams, which can really be supportive for the designers seeking a less vulnerable design. The assessment with this method however, being performed "manually", is a laborious task that also requires the experience of a skilled vulnerability engineer.

Strengths	Weaknesses
• Able to assess compliance of systems	• Laborious and time consuming to perform
• Flexible level of detail	• Requires skilled vulnerability engineer
• Potentially limitless computational power	
• Somewhat reusable for similar systems	
• Provides design rationale	

Table 6.3: Strengths and weaknesses FCA

6.4. Methods comparison

In the above section, different methodologies that could be implemented in the goal tool have been discussed. In this section these approaches are compared by mean of a matrix, in order to assess which one is the optimal method to be employed. For sake of precision, in the evaluation the strength of every approach in meeting the requirements is graded with a 0 to 3 scale. In this connection, 3 stands for a strong ability in meeting the requirement, 2 stands for an adequate ability, 1 means that the approach is barely able to meet the requirement and 0 that it is unable to meet it. Below the comparison matrix is reported:

			Methods		
			Markov Chain	**FTA & LFT**	**FCA**
Requirements	Essential	Ability to assess design	**1**	**3**	**3**
		Sufficient computational power	**0**	**2**	**2**
		Low level of detail in design	**3**	**3**	**3**
		Quick and easy to apply	**1**	**1**	**0**
		Reusable	**2**	**0**	**2**
	Optional	Providing insight of possible criticalities	**1**	**2**	**3**
		Providing hints for design improvements	**1**	**0**	**3**

Table 6.4: Comparison matrix: requirements and possible solutions

As it is possible to notice in the comparison matrix (Table 6.4), none of the approaches discussed in the above section results able to satisfy all the requirements for the evaluation tool. From this analysis it is concluded that a new approach has to be developed in order to meet all the essential requirements and, possibly, also the optional ones. In the following chapter, the main features of the method proposed are presented.

7

Proposed Solution

From the analysis of the possible methods to be implemented in the assessment tool in Chapter 6, it resulted that no suitable approach is available in literature, since none of them can satisfy all the requirements for the tool. Therefore it has been decided to develop a different approach, taking inspiration from the most valid features of the methodologies analysed. In the following paragraphs the most useful features of the methods studied, which can be implemented in the new approach, are described. Subsequently, the main concepts of the new tool are proposed.

7.1. Useful features of analysed methods

Among the best features and concepts that can be implemented in the new approach there are:

- Link from capability to systems (as for vulnerability assessment methods). Instead of analysing the compliance system by system, all the system necessary for a certain functionality (e.g. sail back to port or support life in Safe Areas) could be grouped. This allows to keep the focus on the goals of the requirements and it is therefore very suitable for performance based regulations.
- Visual representation of the systems in blocks (as FCA and partially FTA and LCT). It provides a complete overview of the elements to be studied, offers a better understanding about the functioning of the system and it indeed allows to have insights on the possible criticalities.
- Diagrams of systems' components without location, as FCA and unlike FTA & LFT. If the diagram represents only the structure of the system and not the spatial placement of the components, this can be used for different layouts of similar systems. It makes the model reusable.

- The visual representation of the ship's spaces, as for the network in Habben jansen et al. (2019)). In the network, only the spatial location of a compartment and the relative position with respect to other spaces is shown. For this reason it is certainly suitable for early stages of the design, when details about the geometry or the dimensions of the spaces might not always be relevant. However, it is essential to provide information regarding the spatial location of the components within the ship and also their interconnections to evaluate the compliance of a system. A representation of the compartmentation of the ship is to be provided next to the diagrams displaying the structure of the system.

Considering the strengths of the methods analysed in the previous chapter, the new approach is delineated.

7.2. Description of the proposed tool

The tool proposed is intended to asses the compliance of the design of the system under SRtP regulations. Since these regulations, as described in the chapters above, require a large amount of systems and a high level of redundancy, the placement of each component has to be performed wisely in order to achieve the compliance. The proposed tool provides support to the designers in the early stages of the process by verifying the correct placement of the components of the essential systems. The main features of the proposed solution are described in the following paragraphs, all the remaining details will be reported during the execution of the project.

7.2.1. Systems diagram

The systems diagrams are the main feature of the proposed solution. Taking inspiration from the Functional Chain Analysis, the diagrams of the systems are derived from the functionalities required to the ship after a casualty, as prescribed by SRtP regulations. From the functionality "sail safely to port" for example, all the systems required to perform it are identified and their components sketched on a block diagram. This allows to have a neat overview of the different components of systems, sub-systems and auxiliary systems that are required to function in order to sail back to port, and to better understand their interdependence. The diagram of the systems, since vessel with similar dimensions are assumed to have similar systems, can be used for different projects. Minor changes in the structure of the systems will be taken into account allowing some flexibility to the diagrams. For example, it could be possible to choose the number of redundant components, e.g. how many generators there are in the ship analysed.

These diagrams will also act as software interface for the users, and designers will be required to fill in the information about the location of the components for every block in the diagram representing a component. The information regarding the position of the components will be provided by the designs available at each stage (either developed in-house or provided by Knud E. Hansen see Section 4.5). The software behind the diagram, in which the compliance criteria of the regulations will be implemented, will notify as output if the redundancy intent of the regulations is met, i.e. if the compliance for the systems analysed is achieved. This process will be carried out for all the functionalities required by SRtP regulations or for all the 14 Essential Systems (see Section 3.4.3). When the compliance of the main systems is verified, the risks in the design process entailed by SRtP regulations are significantly mitigated.

7.2.2. Ship division

A fundamental part in the assessment process with the proposed method is the division of the ship in spaces. As it has been said in Chapter 4, one of the first task in the design of a ship is the compartmentation of the vessel. As the design process goes on, the division of the ship becomes more detailed and the characteristics of each space are defined. It is essential however, to organize the information regarding the number of compartments and their characteristics in order to allow the tool to analyse them. Since the input of the software is the location of each component, all the compartments of the vessel must be labelled and their characteristics implemented in the software. It is important indeed, that the "type" of space is described, whether for example it could be origin of a fire or of a flooding (according to the prescriptions of the regulations see Paragraph 3.4.1), or if it is a watertight compartment or a fire boundary and all the other relevant information to make the assessment possible. Also a visual representation of the division in spaces of the ship will be necessary to simplify the task.

7.2.3. Solutions provided by the tool

Once the diagrams of the systems have been filled in with the data regarding the location of the components, the software will assess if the redundancy level required by the regulations is met or not. If the compliance is not achieved, the issue will be reported and the designers will be informed on the type of problem. If, for example, the problem is the placement of two redundant components in the same compartment, the designer will then change the position of one of them in the GA and, by updating the new location in the software, he will be notified if the compliance is achieved. Since the software knows where it is not possible to place the redundant component, the tool could also suggest different compartments where the component can be moved without affecting the compliance. In this way a set of possible design solutions are proposed, and an optimal one might be selected by the designer. Another possibility to achieve the compliance, instead of moving the component to another space, might be the alteration of the space itself. In this connection, the solution would be "protecting" the redundant component adding a fire protection to the space (e.g. A60 insulation or FFF system). In this way the component would be safe in case of the spreading of a fire and the compliance achieved without changing the layout of the system.

8

Proof Of Concept

The goal of the Proof of Concept phase is to determine the assessment logic that the tool should apply in order to verify the compliance of the systems. To achieve this, first of all, it is essential to analyse the types of systems that are installed on board. Indeed it is necessary to understand if a common assessment logic is applicable for every type of systems required by the regulations or if a different assessment logic is needed for each system. Once the assessment on the types of systems has been performed, one simple system will be selected for the small scale model. The implementation of a small model in this phase is necessary to verify that an assessment of the compliance with the proposed tool is possible and to get acquainted with the coding language that has been chosen for this project. All the tasks performed during this phase are reported in this chapter.

8.1. Choice of coding language

The choice of the coding language is a relevant part of the project as it is the means by which the potentiality of the tool can be effectively shown. The most important requirements for the coding language are:

- the large computational power, necessary to deal with a significant amount of data;
- the availability of well developed user interfaces, since the diagrams of the systems are a fundamental part of the proposed tool and must be integrated in the model.

The coding language that has been selected is Python, an open source programming language, very common in the recent years and therefore well supported by a large community of users. Moreover, Python is a powerful language, with great flexibility and versatility and with extensive libraries available. To develop the interfaces of the tool, QT Designer has been chosen for its great potential, the ease of use and of course, the compatibility with Python thanks to PyQT5 (a set of Python bindings for QT designer).

8.2. Analysis of the systems to be installed on board

An accurate analysis of the systems required to be complaint with Safe Return to Port regulations has been necessary to evaluate the possibility of a generic assessment logic for every system to be installed on board. Due to the large structural differences between the systems required by the regulations, a common logic soon appeared to be impossible. However, it has been possible to group the systems into categories with similar assessment strategies. The three families of systems sharing a common assessment approach are:

- **Duplicated Systems.** Many of the systems required to remain operational in casualty scenarios must be fully duplicated to achieve the compliance with the regulations. Propulsion & Steering, Navigation, Fuel Oil system, Power generation and all its auxiliary systems are duplicated systems. All these systems are composed by two subsystems (A and B), they can be arranged in dedicated spaces but they are not always fully segregated. Other than the ones that must be duplicated, it can often happen that other systems might be required to be duplicated by the owner. The assessment logic for this family of systems can be defined as "standard", i.e. it is the same logic for every system of the category. The assessment procedure consists in verifying that for every casualty scenario, at least one of two subsystem remains fully operational.

- **Systems with general service.** Systems like Communication, Fire Main, Fire & Flood detection, Lighting have to be available in many different locations in the ship. Due to the large differences between the structure and the spatial disposition of these systems, a single assessment logic for this family of systems is not possible. However, since the requirements for this systems are fixed, an assessment logic valid for the same system in different projects might be drafted. In addition, some similarities could be found in the assessment procedures of most the systems in this category and therefore the logic for the evaluation of their compliance can be defined as "semi-standard", i.e. not valid for every system in the family but possibly valid for the same system in different projects. The assessment principle for the systems in this category consists in verifying that in every space not affected by the casualty the system remains operational, meaning that all the components must be connected with the main elements (e.g power sources or pumps) and that not all the redundant components are lost in the casualty.

- **Systems with different operational mode in casualty scenario.** There are systems for which the regulations prescribe the possibility of a different operational mode in emergency scenario. The Sewage system for example, has to remain operational in case of a casualty for the passengers accommodated in the Safe Areas on board. In this scenario however, black water can be discharged in the sea instead of being treated as it is normally prescribed. For systems like this, a common assessment logic is clearly not possible and it is very difficult to delineate even some common principle since the operational modes of these systems can significantly change according to the owner's requirements.

8.3. Selection of the system for the small scale model

A system of the second category has been chosen for the implementation of the small scale model of the Proof of Concept phase. The reason for which a system of the second family has been preferred to a system belonging to the first category is because with a simple space definition, the assessment of systems of the first category would be trivial. Indeed with the simplest space definition, namely with only the Main Vertical Zones of the vessel defined, a small duplicated system would not have been challenging enough to prove the utility of the tool. The assessment of the compliance of duplicated systems in facts, becomes a complex task with the increase in the level of detail in the space definition and with the growth of the number of components analysed. Since in the Proof of Concept phase the space definition has not yet a great level of detail, a system of the second category was deemed a better option to prove the rationale of the tool with the correct grade of complexity for this stage.

Among the systems of the second category the Bilge system has been selected, because more information about the structure and the layout of the system was available. In Figure 8.1 it is depicted an outline of the Bilge system. The diagram, extracted from an early stage document describing the design philosophy of the system for a previous project of the Company, was used to define the components to be assessed and to set the level of detail for the small scale model. The components analysed in the proof of Concept Bilge system model are:

- Lines & Suction points;
- Pump sets;
- Valves to close the line in the compartment before;
- Valves to close the line in the compartment after;
- By-pass lines.

As previously mentioned, the spaces defined for the assessment of the systems are the Main Vertical zones of the vessel, neglecting the compartments enclosed. This is certainly convenient to maintain the proper level of complexity for the Proof of Concept phase but it is not, in fact, an approximation. Indeed, the bilge system has to remain operational for casualty scenarios exceeding the casualty threshold (see Paragraph 3.4.4), namely considering a whole MVZ lost, disregarding the compartments inside. For this reason, defining only the Main Vertical Zones for the assessment of the Bilge system is theoretically accurate.
The Proof of Concept model will be able to receive as input which components are installed

in every MVZ of the project and, according to the assessment criteria explained in the following paragraph, it will assess if the layout chosen for the system and its structure are compliant with the Safe Return to Port regulations.

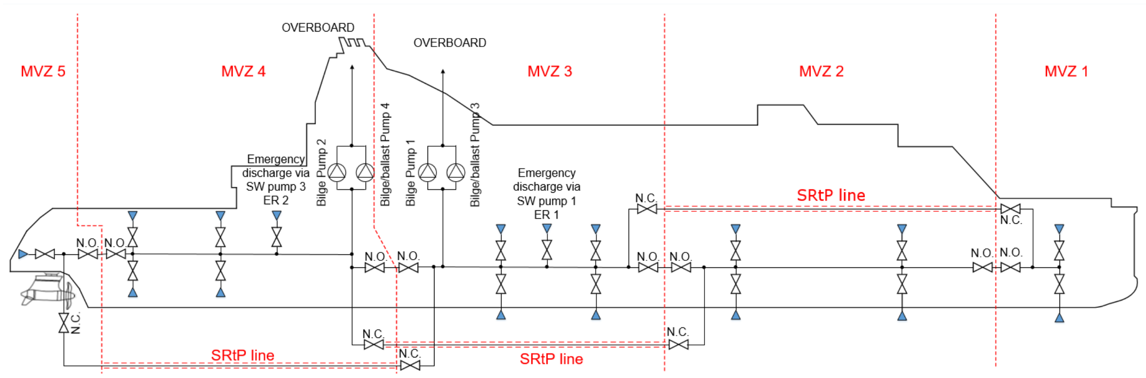

Figure 8.1: Bilge system, structure and layout - (DAMEN's project, 2019)

8.4. Assessment logic for the Bilge System

The requirement for the Bilge system according to SRtP regulations is that the system has to remain operational in casualty scenarios exceeding the threshold in all the spaces not affected by the casualty. In other words, the Bilge system has to function in all the Main Vertical Zones of the vessel excluding the one that originated the casualty. Therefore, to assess the compliance of the system, it will be necessary to verify that the lines and the suction points in every MVZ not affected by the casualty are connected with at least one serviceable pump set. Every component located in the MVZ affected by the casualty is to be considered lost with the exception of lines with no valves and joints provided with A60 fire protection, as prescribed by the regulations. For the small scale model, by-pass lines are considered to meet these requirements and therefore they remain available even when passing through the unserviceable MVZ. Once the components in each Main Vertical Zone have been input, the tool will apply the assessment logic to verify the compliance of the system. The flow chart in Figure 8.2 illustrates the assessment logic that is applied. The tool will first verify that at least two pump sets have been installed in the project, then, considering one at the time all the MVZ lost, it will verify that the essential components have been installed and that the loss of the MVZ does not interrupt the service in the other zones of the vessel.

8.5. Small scale model

The small scale model is the implementation in Python of the logic outlined in Figure 8.2. The model is provided with two simple but effective interfaces. The first one is the Main Window (Figure 8.3), in which the user is informed on how to divide the ship for the as-

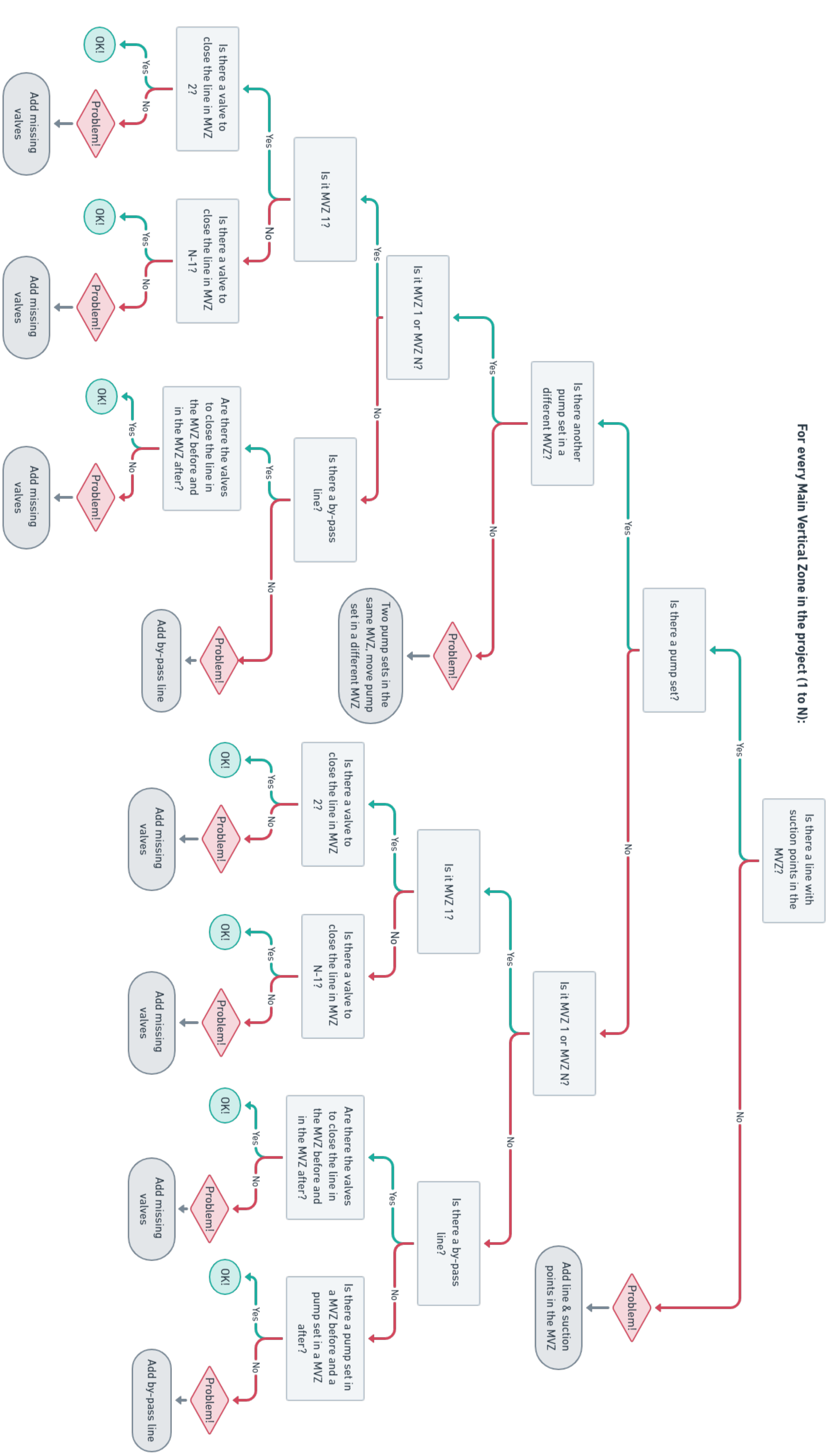

Figure 8.2: Assessment logic Bilge system - Proof of Concept

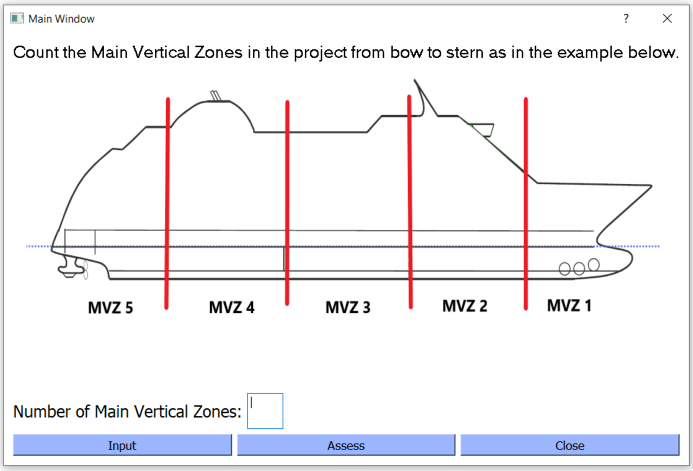

Figure 8.3: Proof of Concept model - First interface: Main Window

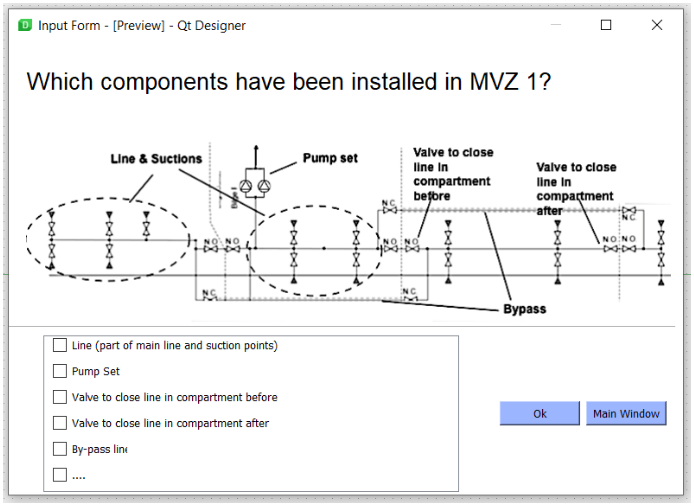

Figure 8.4: Proof of Concept model - Second interface: Input Form

sessment and the number of Main Vertical Zones in the project is required as input. Once the user has identified the MVZs and orderly named the MVZ in the project, it is possible to open the second window with the interface dedicated to input of the data. Figure 8.4 shows the input interface in which the user can fill in the components of the Bilge systems installed in the Main Vertical Zone by means of a check list. The input interface is provided with a diagram of the simplified Bilge system to guide the user in the selection of the components to input. An Input Form will be shown for every Main vertical Zone in the project. Once the input phase is concluded, by clicking the "assess button" in the Main Window, the tool will apply the logic previously explained and the compliance of the system will be evaluated. If the system analysed is not compliant, the tool will report the issue with a message box indicating the type of problem found and the location (in Figure 8.5 some examples of message boxes). The messages of the issues will also be printed in the command window as shown in Figure 8.6, to allow the user to visualize them permanently.

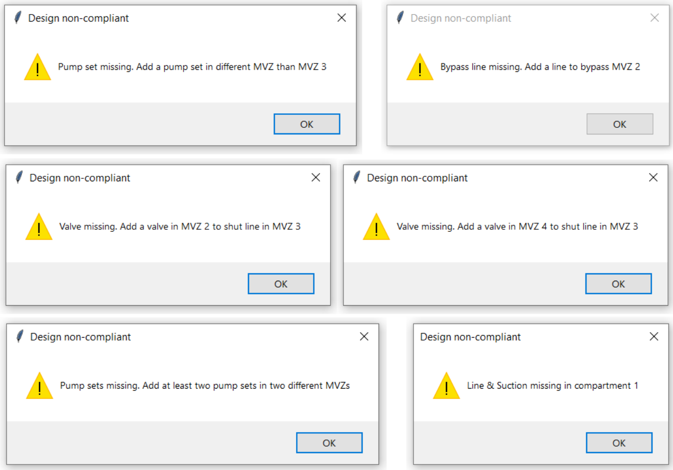

Figure 8.5: Proof of Concept model - Examples of Message Boxes reporting the issues

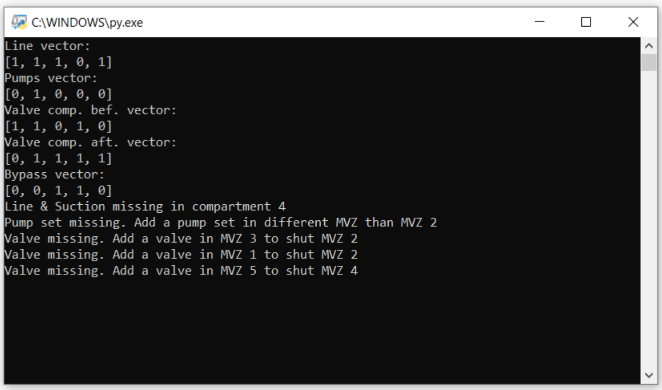

Figure 8.6: Proof of Concept model -Prompt window: output

8.6. Results of the Proof of Concept model

Once the assessment logic has been successfully implemented in the programming language and the small model finalized with the interfaces, it has been tested with various layouts of the Bilge system. The tool modeled is deemed capable to determine whether or not the Bilge system can remain operational in case a Main Vertical Zone is lost as a result of a casualty. The tool will effectively notify the user if the compliance is not achieved, conveniently displaying the type of issue in the design of the system. Furthermore, when a pump set is missing or when two pump sets have been placed in the same MVZ, the tool can also suggest where is not possible to install/move the redundant component. Even if this feature is not very useful when just the Main Vertical Zones are defined since the solution is straightforward, it has been implemented to test its feasibility in more complex scenarios. All in all, the tool is deemed to work as planned and it is therefore possible to proceed with the implementation of larger models.

8.7. Expanding the model

The development of the Proof of Concept model was also important to understand what are the challenging aspects needed to be addressed for the expansion of the tool. The first consideration about the small scale model concerns the modality of input. For the Proof of Concept model, selecting the input through a check list was deemed more intuitive for the simplified scenario. While scaling up the size of the systems and increasing the level of detail for the space definition however, such an approach is not preferable anymore. Indeed it is not convenient to have an input interface for every space in the ship when dozens of compartments are defined and many components of different systems may be installed inside. A sort of "System-diagram interface" will result more convenient to indicate in which compartments are the components analysed, simplifying the input process.

Another aspect that is crucial to address for the expansion of the model is the procedure for the detailed space definition. Indeed, it must have the sufficient level of detail to allow a correct assessment of the compliance but at the same time it should not require information too detailed for the early stages of the design process. Another challenging aspect that needs to be considered before scaling up the model is how to properly deal with the large amount of data that a model with larger systems and detailed spaces requires. In this connection, the implementation of the Proof of Concept model in Python allowed to get acquainted with the programming language and to find some of the solutions to the practical problems that coding a more complex model will arise. Lastly, it has to be figured out how to suggest where to move components in case of conflicts in the design with a more detailed space definition, and the strategy for every other solution that it may be desirable to provide.

To conclude, the Proof of Concept model was necessary to prove that a tool for the assessment of the compliance with SRtP regulation is possible but it was also necessary to define the challenges in the implementation of a larger and more complete model. A different mode of input, a wise formulation of the space definition and the strategy to propose the solutions must be addressed before the expansion of the model.

9

Large scale model

Once the Proof of Concept phase is concluded, the large scale model for the graduation project can be implemented. In this chapter the method for the mitigation of the risks entailed by SRtP regulations developed is explained. The method is composed by the space definition and by the assessment performed by means of the software tool. First, the detailed space definition, necessary for the assessment of the compliance also in the SRtP scenario, is described. Subsequently, the development of the tool for the evaluation of duplicated systems is reported.

9.1. Space definition

The definition of the spaces on board is an essential part of the design process of every project in the shipbuilding industry and it becomes even more important in the design of Safe Return to Port projects. The space definition has to be delineated since the very beginning of the process and it must include all the relevant information for the design and for the assessment of the systems on board.

9.1.1. Purpose of the space definition

The definition of the spaces on board is considered the basis of the design of Safe Return to Port projects [19] because it is indispensable for the correct arrangement of all the systems (components, piping and cabling). The space definition in SRtP project is often referred as "Casualty Threshold plan", a fundamental document that describes location, extent and identification of all the possible casualties on board. This type of document should be drafted at the very beginning of the design process when the first spaces are defined on board. As the design process goes on, the Casualty Threshold plan will likely change, as more details about the spaces are available and also alterations to the original spaces might have been carried out. For example, the installation of a fixed fire-fighting system in a fire boundary would modify the extent of a fire casualty originated in that compartment, clearly modifying the Casualty Threshold plan. In a different scenario, a space that was originally considered of negligible fire risk ,e.g. because empty in the early stages, could then accommodate components in a later stage, altering the risk of originating a fire casualty. Therefore, it is essential to properly draft this type of document at the beginning of the process for the design of the systems, but it is also important to keep it updated for the assessment of their compliance.

9.1.2. Space types & attributes

Since the space definition is an essential part of the evaluation of the compliance, it is clearly also a fundamental step in the assessment of the systems by means of the proposed method. The space definition needed for the tool to perform, is in line with the Casualty Threshold plan above mentioned. The space definition can vary with the level of detail in the design, in order to be applicable to every stage in the design process. In this section all the types of spaces necessary for the assessment of the compliance of the systems installed on board are described. The spaces will have different characteristic and attributes that must be well clear in the mind of the designer at the moment of the assessment. The spaces required by the tool to perform the evaluation of the compliance are:

- **Main Vertical Zones**.The MVZ are the lowest level of detail possible for the definition of the spaces and they will be given as input when no other spaces have been defined, for a preliminary assessment of the system. Alternatively, the assessment will be performed on the definition of the MVZ only, when the system is required to remain operational in scenarios with casualties exceeding the threshold, as in the case of the Bilge system analysed for the Proof of Concept (see Section 8.3). The Main Vertical Zones are also an attribute of other spaces, if these are defined on board. In other words, the tool requires that the more detailed spaces defined on board are located in a certain MVZ. Indeed it is necessary to define in which Main Vertical Zone is a certain compartment in order to locate different spaces within the ship and to be able to perform a correct assessment of the systems. The input of the MVZ as attribute will be explained in Section 9.2.

- **Watertight compartments**. This type of space is the key element for the evaluation of flooding scenarios within the casualty threshold. The watertight compartments are defined as any compartment below the bulkhead deck limited by watertight bulkheads. All the watertight compartments below the bulkhead are considered of risk of flooding, regardless the distance from the hull. The watertight compartments will require as attribute the MVZ and the deck (i.e. each watertight compartment defined must be placed in a certain MVZ on a certain deck).

- **Fire boundaries**. The Fire boundaries are the spaces identified for the evaluation of the fire casualties within the threshold. The fire boundary is defined as any compartment limited by A0 fire protection. Fire boundaries can also be protected by a fixed fire-fighting system (FFF). In this case, the fire would not spread out to the fire boundary which originated the casualty. Information about the installation of the FFF system in the compartments is therefore essential to assess the extent of the fire. Similarly to watertight compartments, this type of space has as attribute the Main Vertical Zone and the deck. Moreover, also the presence of a fixed fire-fighting system in the space is required as attribute, in order to properly assess the spreading of the casualty.

- **Trunks**. Trunks are spaces with their own assessment rules and they must therefore be analyzed separately. There is not a generic definition of "trunk" but they are usually spaces dedicated to the routing of pipes and lines. Trunks can be arranged horizontally, e.g. connecting different Main Vertical Zones, or vertically, if they connect different decks. Trunks can be spaces of negligible fire risk if they contained only pipes with non-flammable liquids and there are no valves nor joints inside the trunk. Unlike fire boundaries, it is important to define the rating of A- fire protection in order to assess the extent of a fire casualty. Trunks provided with A60 fire protection in fact, even if possibly origin of fire, would not allow the fire to spread out to the space and a fire originated in an adjacent compartment would not affect the trunk if A60 fire protection is installed. It is therefore essential to indicate whether the trunk is provided with such a protection as attribute of the space together with the other standard attributes: MVZ and Deck.

- **Generic spaces**. As the name of the space explains, this category groups all the other spaces that cannot be origin of a casualty (e.g. void spaces, cofferdams, tanks, chain lockers etc.). It is still important to define them for the sake of the assessment since they can still be affected by a casualty that spreads over the area. Like watertight compartments, Generic spaces have Main Vertical Zone and Deck as only attributes.

The spaces described above are the ones necessary for a correct and sufficiently detailed assessment of the compliance of the system based on the space definition. Clearly on a ship many other types of spaces, different for purposes and characteristics, can be defined. The five spaces identified above however, are deemed to be a more than satisfactory approximation of the space division, which does not neglect the major details for a correct assessment of the casualties and their possible consequences on board.

9.1.3. Space definition: rules & assumptions

Some rules on the space definition have to be set and few assumptions have to be made in order to optimize the effectiveness of the tool. The first one important to mention is that every space defined above, with the exception of generic spaces and trunks with negligible fire risk, are considered to originate a casualty according to the assessment logic applied by the tool. As a watertight compartment or a fire boundary are defined in input, they will be considered one at the time origin of a casualty. When the assessment for casualty beyond the threshold will be selected, the same principle applies for Main Vertical Zones. Spaces for which this principle does not apply must be defined as Generic Spaces. This is an important rule to take in mind while identifying the spaces for the input in the tool.

Another important rule for the definition of the spaces concerns casualty boundaries inside other casualty boundaries of the same order. It might happen for example, that below the bulkhead deck the extent of a fire might differ from the extant of a flooding in the same area. In terms of the space definition, this corresponds for example to fire boundaries inside watertight compartments (Figure 9.1). Even if would be intuitive to define just the largest casualty threshold for the same space, it is essential to define every casualty boundary in the area to cover all the potential issues. In the scenario sketched in Figure 9.1, two fire boundaries provided with fixed fire-fighting system are located inside a watertight compartment. If the fire boundaries are assessed separately, assuming the two compartments contain components of different subsystems, no issue would be reported by the tool since any fire casualty originated in F1 and F2 would not affect the operation of both subsystems. If instead, the design would be assessed for largest casualty of the area (i.e. flood casualty in W1), the components of both subsystems would be lost and the compliance not achieved. However, if just the flood casualty threshold in W1 would be analysed, the possibility of the fire spreading outside the watertight compartment in the case the fire boundaries were not provided with FFF system would be neglected. It will therefore be required to define every casualty boundary, even when located inside another boundary.

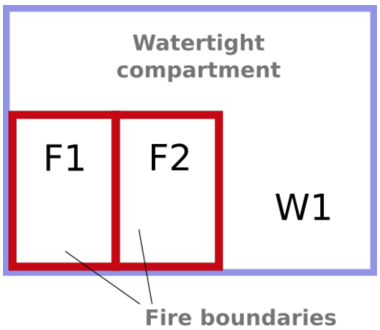

Figure 9.1: Example of fire boundaries inside of watertight compartment

Another assumption that has been made to simplify the input process concerns lines, pipes and cables. In this connection, when a line connects two components in the same compartment or in two adjacent compartments, it will not be necessary to specify the location of the line. When the components that connects are located in two non-adjacent compartments however, it is required to input which spaces the line crosses for a correct and complete assessment of the compliance. In this case, the line is to be considered passing through the compartment in between, neglecting the compartment of origin and destination. In Figure 9.2 the assumption about the input of the position for lines, pipes and cables is depicted. In the situation sketched in Figure 9.2 for example, Line 1 will be considered to cross compartments C3 and C4 and they have therefore to be input as compartments in which Line 1 is located, neglecting the compartment of origin and destination (C5 and C1).

For the case of Line 2 instead, there will be no need to input the position of the line for a correct assessment, since it connects components into two adjacent compartments. Indeed, if there would be an issue with one of the two compartments of Line 2, also the component that connects would be misplaced, being part of the same subsystem. If the component is moved elsewhere, the line would not remain in the compartment, unless to cross it in order to connect the component that has been positioned in a space not adjacent to C2. As explained already, in this case the location of the line must be specified. Clearly, information about lines and routes will be input only if this type of information is available at the current stage of the design (otherwise it is possible to assess only the correct placement of the components).

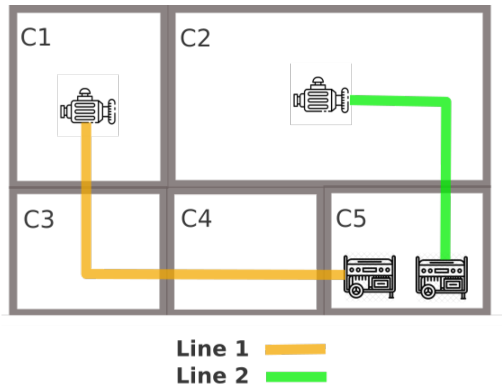

Figure 9.2: Assumption input location lines, pipes and cables

9.2. Input process

When all the spaces on board have been defined, it is possible to perform the assessment on the arrangement of the desired systems. To do this, it is necessary to indicate in which compartments are located the components of the system, making sure to specify all the characteristics and the attributes of the space analyzed. The input required by the tool is structured as depicted in Figure 9.3.

Figure 9.3: Structure of the input for spaces

The first entry represents the type of space. The different options, according to the space definition reported in Section 9.1.2, are:

- **M**, for Main Vertical Zones. Given as input when the user wants to perform an assessment for casualty exceeding the threshold and just the Main Vertical Zones have been defined (lowest level of detail);

- **W**, for Watertight compartments;
- **F**, for Fire boundaries;
- **T**, for Trunks;
- **G**, for Generic spaces;

The second input represents the Main Vertical Zone while the third one the deck. If a watertight compartment is located in the second MVZ on the first deck for example, the input will be "W21". The fourth entry stands for the number of the compartment. This will be necessary if in the same MVZ on the same deck there are more spaces of the same type. The input for the third fire boundary located in MVZ 2 on deck 4 would be "F243". The last entry is required for the additional attributes of spaces like fire boundaries and trunks. In case of fire boundary, the additional attribute will define if a fixed fire-fighting system has been installed in the space ("P" if it has been installed and "0" or empty if it has not been installed). For trunks it will be "0" or empty if the trunk is not provided with A60 fire protection and "P" in the opposite situation. To make an example of this last scenario, the input for the only trunk situated in MVZ 5 on deck 2 provided with A60 protection is "T521P". The fifth input, only in the assessment for casualty exceeding the threshold and if just the MVZ are defined, can also be "R" for components that can withstand different casualties. When the fifth entry for a component is "R", the element is not considered unserviceable in any casualty scenario.

The information about the type and attributes of the space in which a component is located will be input as a string in a label underneath the component in the interface illustrating the diagram of the system. If there is the need of indicating more compartments for a single component, e.g. for a line passing through different spaces, or to specify that the component is in a casualty boundary inside another boundary (as for the example in Figure 9.1), it is possible to input the strings defining the different compartments separated by a comma. Assuming that in the example sketched in Figure 9.2, C3 and C4 are the only two fire boundaries in MVZ 3 on Deck 4 without fixed fire-fighting system, the input string for Line 1 would be: "F3410,F3420".

The possibility of input more compartments for a single component will also improve the flexibility of the tool. If in the project analyzed more redundant components than the ones depicted on the interface diagram have been installed, it will be possible to indicate where the additional components have been installed by adding more compartments as input for the component in the diagram. This feature, required for the correct assessment of the systems, also enhances the flexibility and the potentiality of the tool.

Another solution that has been applied to further simplify the input process is how it has been chosen to input the information about the proximity of the compartments. Indeed, to perform a complete assessment is required to know the relative position of the spaces on board and, even if the attributes MVZ and Deck of each space allow the tool to group the spaces with identical attributes in a precise area, there is no information about the adjacency of the compartments. However, this kind of information is essential to assess, for example, how and where a fire casualty originated in a certain room spreads. Instead of filling this input data before the assessment process, it will be required at the moment of the evaluation exclusively if needed for the compartment for which is needed. This solution, speeds up significantly the input process and allows the tool to elaborate just the relevant information. The input of the information regarding the relative position of the compartments will be examined more in depth in the following chapters.

It is also important to mention the input process for "casualty resistant" material installed on board. As it has been already explained in the previous chapters, there is the possibility to install on board components that can withstand casualties. Examples of these are steel pipes with certain characteristics, fire resistant cables or shaft lines and other material if specifically certificated and tested (a more detailed description is reported in Section 10.2). If the choice of using this type of components is known since the very early stage, it would be important to specify this characteristic in the input for the assessment. In fact, if a line passes through a compartment where there could be an issue, the tool would notify the non-compliance of the system since it would be lost in case of a casualty. If the material could withstand the accident however, it would not be an issue for the compliance, as it would remain operational after the casualty without any additional protection. Knowing this however, instead of specifying if the material can withstand a casualty, it has been decided to neglect the component in the assessment, as no wrong placement for it is possible. With this choice the input phase is further simplified, since an additional attribute would have been required, and the precision of the assessment of the compliance is not affected. Every line that is known to resist casualties at the moment of the assessment is therefore not required to be implemented as input, as the compliance of the system does not depend on its position. The possibility of indicating casualty resistant components in the assessment for casualty exceeding the threshold has been left, even if negligible, as no additional attribute for the space was required in the assessment.

9.3. Choice of the model

Once the effort needed to design and implement a sample of the software tool has been defined during the Proof of Concept phase, it is possible to select the extent of the project to develop for the Master thesis. In this connection, it has been chosen to implement a model for the systems of the first category (see Section 8.2). This choice has been made for different reasons. First of all, since the systems in the first category share a single assessment logic, by developing a tool able to assess a system of the first family, every system in that category could be tested with the same software. This is deemed to bring great advantages, especially during the testing of the tool, when it will be possible to assess a variety of systems. The second reason is because, as it will be explained in this chapter, the assessment of duplicated system is strictly reliant on the space definition. Since the definition of the spaces on board is the basis of the design of all the systems on board, this is also essential in the evaluation of their compliance. Developing a tool based on the space definition therefore, could be considered as a "solid ground" on top of which assessment tools for systems of different categories can be built. It is deemed in fact, that the other assessment tools will heavily rest on the basis on the model for duplicated system that could be considered, for this reason, a sort of "parent" model. Lastly, provided a limited time span for the graduation project, a choice on the extent of the model is necessary, and a single program able to assess multiple systems is deemed to have greater academic value and it is also very useful during the testing phase. In this chapter, the implementation of the big scale model, from the division of the ship in spaces to the description of the major features, is explained.

9.4. Generic assessment logic for duplicated systems

In this section the rules applied by the tool for the assessment of the compliance of duplicated systems are reported. As it will be possible to notice, the assessment rules are mainly dependant on the spaces and their characteristics. This is considered the major strength of the tool that is, for this reason, applicable to all the systems of the first category (see Paragraph 8.2). The assessment of the compliance will be based on two scenarios, as prescribed by the regulations: for casualties within the threshold and for casualties exceeding it. The user, once filled the input data in the software, will be able to test the compliance for the preferred scenario. The choice of the scenario for which testing the compliance of the system can be selected according to the regulations (systems required to remain operational also in OEA scenario) or according to the owner's preferences. It might in fact happen that a system not required to function for casualties exceeding the threshold by the regulations is instead required to remain operational by the owner. Assessing the compliance of the systems for the desired extent of the casualties has been made possible with the proposed tool since the testing scenario is not implemented according to the requirements of the regulations for each system but it is a choice of the user.

9.5. Assessment for casualties beyond the threshold

As explained in Section 8.2, the principle for the assessment of duplicated systems is verifying that for all the casualties of the chosen extent possible, at least one of the sub-systems remains operational. The assessment for casualties exceeding the threshold consists in considering one at the time all the MVZs lost and verifying that not both subsystems are affected. In Figure 9.4, the process for the evaluation of the consequences of casualties exceeding the threshold is illustrated in a flowchart. Components placed in special compartments like trunks provided with A60 fire protection are considered to remain operational even in the Main Vertical Zone affected by the fire. Furthermore, if just the MVZ are defined, there is the possibility of indicating if the components installed are "casualty resistant". Therefore, if a component can withstand casualties, it will be possible to input "R" as fifth entry of the string defining the input (see Paragraph 9.2), and it will not be considered "critical", even if mislocated.

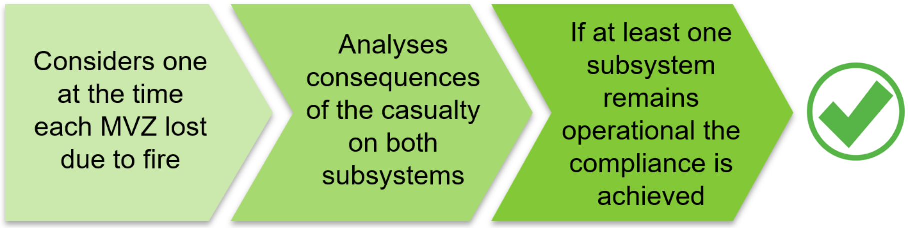

Figure 9.4: Evaluation process for casualties exceeding the threshold

In any other case in which a component is wrongly positioned, the tool will notify that the system is not compliant, reporting what and where is the cause of the issue. Here is an example of the notification printed in the command prompt:

"If MVZ 1 is lost, both subsystems are affected. There are 1 components of Subsystem A (['Engine 1']) and 1 components of Subsystem B (['Generator 2']) not protected. Some components must be moved"

With the notification of the issue, the user will also be informed on possible solutions to be implemented in the design in order to achieve the compliance. The solutions proposed by the tool in every scenario will be explained in the following chapter.

9.6. Assessment for casualties within the threshold

Even if the systems required to remain operational in casualty scenarios not exceeding the threshold grant a lower level of "survivability" than OEA systems, their assessment is arguably the most difficult to perform. The reason after this is because this assessment is based on the more detailed space definition and all the characteristics of the spaces must be taken into account in order to properly carry it out. In this section, the type of assessment performed for the different types of space is presented.

9.6.1. Watertight compartments

For the assumption explained in Paragraph 9.1.3, every space in the ship that can be origin of a flooding casualty will be defined as such. The assessment for this type of space will simply consider one at the time all the watertight compartments affected by a flooding, and it will be verified that the casualty does not affect the functionality of both subsystems. Since the flooding casualty is not considered to spread into other spaces the assessment for this type of casualty is limited to the evaluation of the subsystem types of the components installed in the watertight compartments.

9.6.2. Fire boundaries

As in the flooding scenario, the assessment for fire boundaries begins with the evaluation of all the components installed in each fire boundary defined as input. Unlike watertight compartments however, it is necessary to distinguish fire boundaries in which a fixed fire-fighting system has been installed and fire boundaries not provided with any fire protection. Indeed, it is essential to assess whether the FFF has been installed to evaluate if the fire can spread into other spaces. For fire boundaries provided with fixed fire-fighting system the assessment is limited to the evaluation of the types of subsystem of the components installed inside. For fire boundaries without FFF, the fire casualty threshold is defined as the loss of the space of origin and the adjacent spaces up to the nearest "A" class boundaries. In this case therefore, the assessment must be extended to the components installed on the same deck and even on the deck above (within the same MVZ).

Once a fire boundary without FFF is assumed to originate a fire, the tool will first assess the components inside the boundary and, when verified that there is only one subsystem type inside, it will search for potentially critical components on the same deck and subsequently on the deck above. The verification of the presence of only one subsystem type within the space it is also necessary for the tool to understand which subsystem type to look for among the components installed on the same deck and on the deck above. If, for example, it is assumed that two components of two different subsystems have been installed within the same fire boundary, the software will be unable to assess which subsystem type should not be placed in the area at risk, as both could potentially be mislocated in the space of origin. If components of different subsystems are found in the same fire boundary not provided with FFF, the assessment will not continue and it will be necessary to solve this issue first.

When the issue has been solved or if there was not any issue, the assessment proceeds with the search for components of a different subsystem among the spaces potentially at risk (i.e. the ones with same MVZ and Deck attributes and the ones with same MVZ attribute and Deck attribute +1). If components that meet the requirements are found, the user will be asked to input information about the arrangement of the two compartments (space of origin of the fire and compartment with components of different subsystem type on the same deck or on the deck above). If the component at risk is on the same deck the user will be asked if the two compartments are adjacent and if the casualty could spread and affect the other room. If the component is on the deck above the user will be asked if the casualty could spread into the compartment above and a picture explaining the criteria for this assessment is shown. This because how the fire spreads from deck to deck is regulated by precise rules and assessing it is not as intuitive as verifying the adjacency of two spaces. In Figure 9.5 the message illustrating how the fire spreads on the deck above is shown.

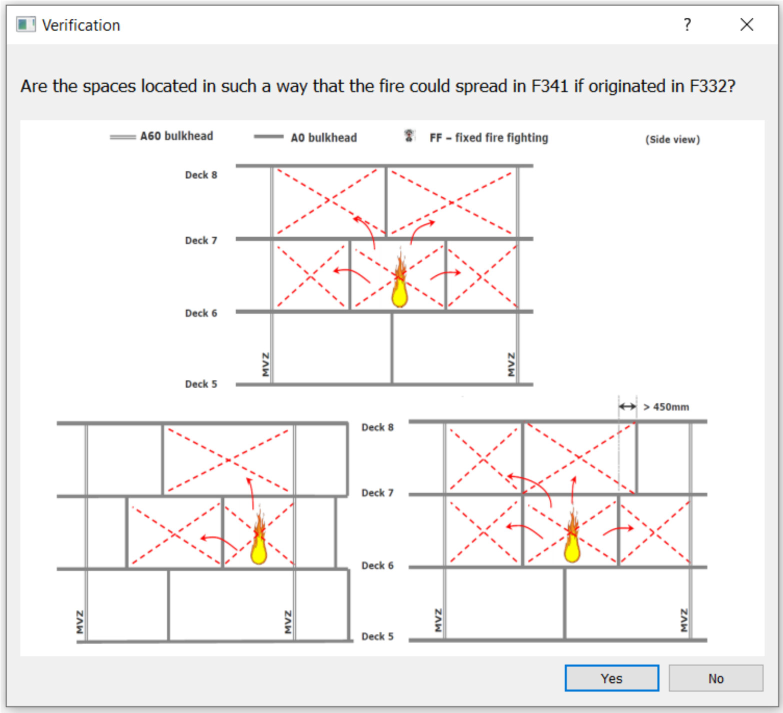

Figure 9.5: Required input for assessment of the spreading of a fire casualty

When information about the relative position of spaces on board is asked, it is stored in the software in order to avoid the same question if, for example, two fire boundaries with components of different subsystems are installed on the same deck. Furthermore, this strategy to input information about the proximity of spaces is very convenient for the quickness and ease of use of the tool, as it is asked exclusively if needed and only for the spaces for which is needed. This also allows the tool to build a sort of "smart network" relating the places with critical components that will also be useful in the assessment of the locations in which is possible to move the components, with another functionality of the proposed tool.

Another important aspect to be mentioned for the assessment of casualties originated in fire boundaries is that it is performed separately for trunks and the other space types. This because it is also essential to consider that trunks provided with A60 fire protection are not considered lost if the casualty is originated in a different space, even when adjacent. For this reason when potentially critical components are found it is first assessed if they are installed into a "Trunk" space type and, if yes, if the trunk is protected with A60 class. When all the information needed for the complete evaluation of the effects of a fire casualty originated in a certain fire boundary have been collected, the assessment is performed. If actual criticalities in the placement of the components of a system are found, the user will be notified with the type of issue (which components are misplaced and where), and some solutions are suggested. It will be suggested to install a FFF system if not already in place or to move the component elsewhere. Below a typical example of issue reported in the evaluation of fire boundaries:

"Install fixed fire fighting system in F412 or move components. A fire casualty could spread into W411 and Generator 1 would be lost"

In Figure 9.6, the process for the evaluation of the consequences of fire casualties originated in fire boundaries is illustrated in a flowchart.

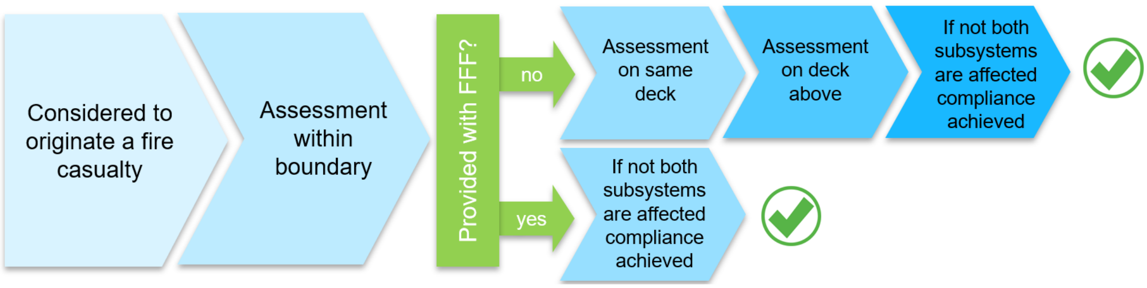

Figure 9.6: Evaluation process for casualties originated in fire boundaries

9.6.3. Trunks

The assessment for trunks is for many aspects similar to the assessment for fire boundaries and therefore only the different aspects will be explained. The major difference is that, unlike fire boundaries, trunks might not be origin of a fire, depending on the characteristics of the components installed inside. If potential criticalities are found inside the same A60 trunk and for every trunk not provided with A60 protection, the user will be asked if the space analysed can be origin of a fire. In Figure 9.7 an example of the verification message is reported. Similarly to the information about the proximity of compartments, also if a certain trunk can be origin of a fire is data that will be stored in the memory of the software for future assessments and for the elaboration of the solutions.

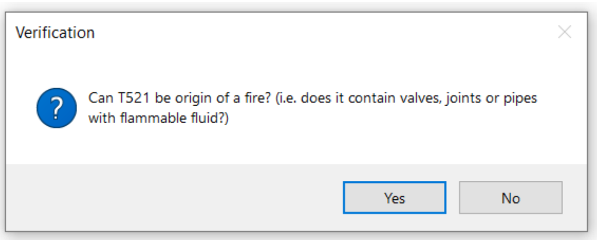

Figure 9.7: Example of verification message - negligible/non-negligible fire risk trunks

As in the case of fire boundaries, the assessment for trunks is also performed differently depending on the value of additional attribute, namely the installation of A60 protection. If provided with A60 fire protection, the assessment will be limited to the evaluation of the subsystem types of the components installed in the trunk. Conversely, if not provided the assessment will be performed for the components installed inside first, and subsequently for the potentially critical components on the same deck and on the deck above, as in the case of fire casualties originated in fire boundaries. In Figure 9.8, the process for the evaluation of the consequences of fire casualties originated in trunks is illustrated in a flowchart. Again, the assessment is separated for trunks and for other space types to correctly take into account all the characteristics of the surrounding compartments. When the assessment is completed, if issues have been identified, they will be notified to the user. An example of the message reporting an issue related to a trunk is:

"Install A60 protection in T561 to avoid the spreading of the fire in G562 or move components (Transformer 2 would be lost in case of fire)."

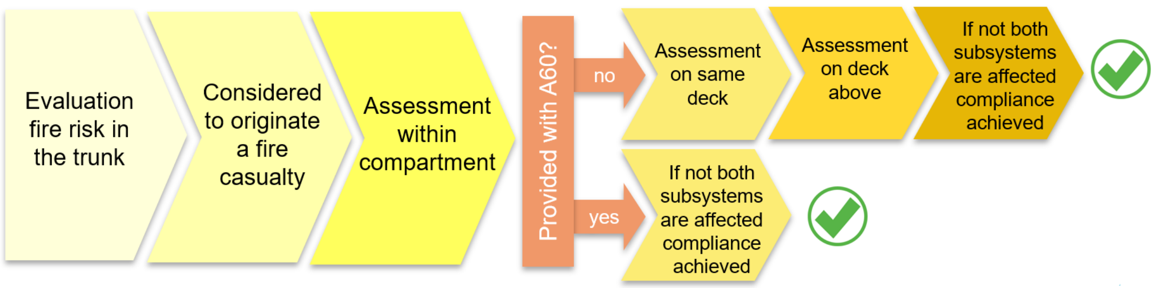

Figure 9.8: Evaluation process for casualties originated in trunks

9.7. Application of assessment method

In this chapter the method comprising space definition and software tool was described. The application process of the method proposed however, must follow specific rules to be effective. For example, the space definition has to be performed clearly before the assessment with the tool to define the input necessary, but it is important to keep it updated whenever new detailed information about the spaces and their characteristics are defined during the design process. If not applied in the correct way, the method will result ineffective for the mitigation of the risks entailed by SRtP, nullifying all its potentiality. For this reason it is essential that the application of the tool follows a specific procedure. In Figure 9.9 a flowchart illustrating the assessment process by means of the proposed method is provided.

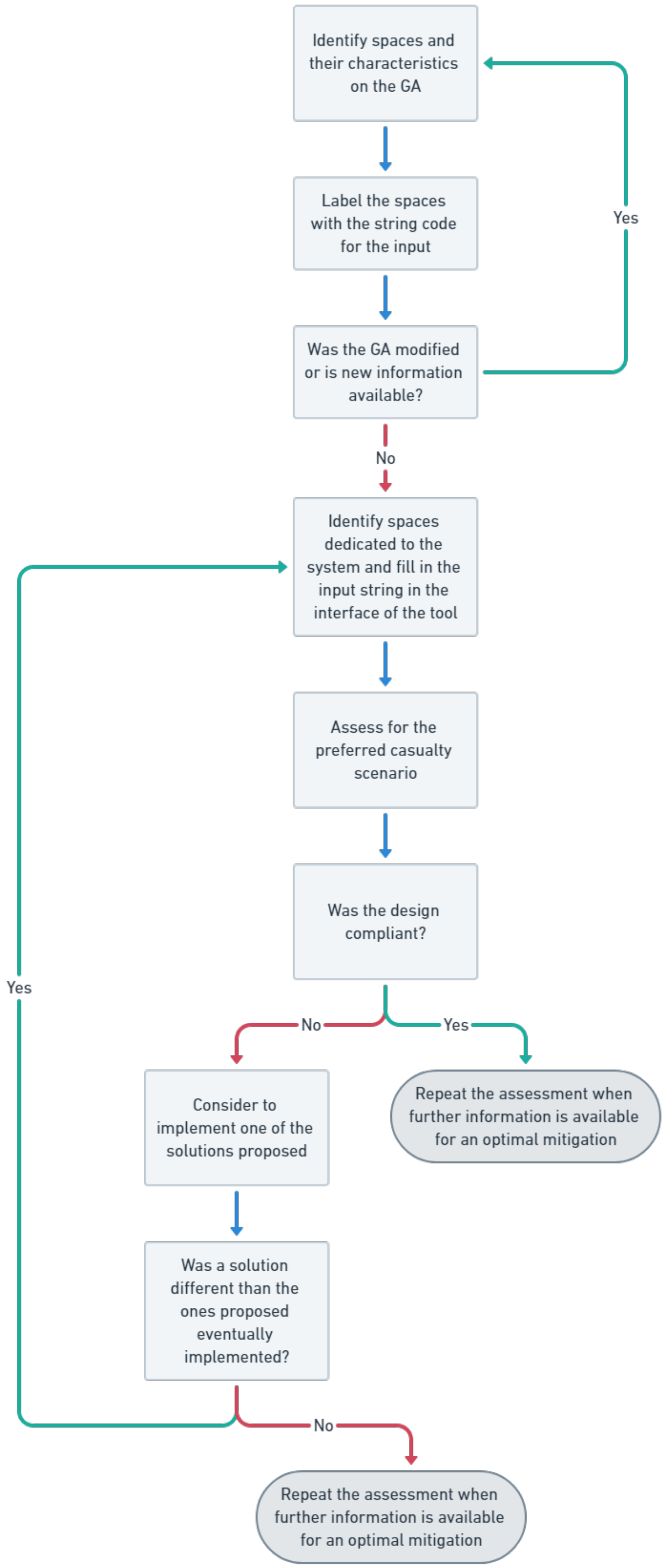

Figure 9.9: Application of the proposed method - workflow

10

Solutions

The goal of the tool is the assessment of the compliance of a system with Safe Return to Port regulations, and it can be effectively performed with the functionality explained in the previous chapter. The tool however, is also able to provide some suggestions on how to achieve the compliance if this is not met in the first place. The solutions proposed are several for every scenario and it is up to the designer deciding which one is the most suitable for the situation analysed. This because the tool would not be able to assess which is the optimal design solution to undertake, as the "optimality" of a design solution is influenced by many different parameters like costs, time, production preferences, owner's requirements, company's inclinations and many other aspects of which is almost impossible having a complete overview. The strategy of the tool is therefore limited to the suggestion of all the possible options for the type of issue that has been reported, leaving to the designer the choice of which one to implement. In this section, all the solutions that can be possibly proposed are reported.

10.1. Protection of spaces

This solution is applicable for the spaces that can be origin of fire, namely fire boundaries and trunks. In case a fire boundary originates a casualty that would compromise the compliance of the system by spreading into other compartments, it is suggested the installation of fixed fire-fighting system. This solution, as already explained, would limit the extent of the casualty to the space of origin, and by doing so, it would solve the problem that caused the system to be non-compliant. An example of the message printed in the command prompt is:

"Install fixed fire fighting system in F123 or move components. It could spread into W121 and Alternator 1 would be lost"

The "protect solution" for trunks consists in the installation of A60 fire protection. While the FFF system has the only goal to avoid the spreading of the casualty outside the space of origin, the installation of A60 fire protection in trunks can be adopted also to protect the components from a casualty originated in a different space. If, for example, a fire originated in a fire boundary could spread into a trunk and affect components of a different subsystem the warning reported would be:

"Install fixed fire fighting system in F452, install A60 protection in T461 or move components (Generator 2 would be lost in case of fire)"

If a trunk is the origin of the casualty compromising the compliance, it would be printed:

"Install A60 protection in T461 to avoid the spreading of the fire in G462 or move components (Pump set 2 would be lost in case of fire)"

or, if it would affect a component located in another non-protected trunk:

"Install A60 protection in T461 to avoid the spreading of the fire outside the space of origin or in T463 to protect the components inside The fire could also spread from T463 to T461 since it can originate a fire and the two compartments are adjacent. Install A60 protection in both compartments.)"

Obviously, if in the second trunk there is negligible fire risk, the user would not be warned for the possibility of the spreading of the casualty from trunk T463 to trunk T461. The protection of spaces by means of FFF system and A60 class insulation is an effective strategy to solve many of the criticalities in the compliance with SRtP regulations, and should always be considered if applicable in case of non-compliant designs.

10.2. Installation of "casualty resistant" material

It has been explained already in the previous chapters that some components can be considered serviceable even when located in a space affected by a casualty. The most common components are lines, which can be considered "casualty resistant" if certificated and properly tested. More specifically can be considered "casualty proof" (according to DNV GL):

- **Pipes**: steel pipes of substantial thickness, no flammable liquids and plastic pipes if tested according Resolution A75318. Also welded joints and mechanical joints have to be tested.
- **Cables**: fire resistant cables passing through (not serving) and tested according IEC 60331. Cables complying with IEC 60092-359 considered to remain operational in a

space affected by flooding.

- **Propulsion shafts**: Shaft lines and bearings may be considered operational even if passing through a compartment affected by a casualty (fire or flooding) on certain conditions, if tested and documented.

In this connection the tool, when it finds an issue related to a line, suggests the user the solution of "upgrading" the material of the line to make it able to withstand a casualty. In this scenario the user will be required to verify that the line meets the conditions listed above before considering the option of the installation of "casualty resistant" material. The notification reported to the user would for example be:

"Install fixed fire fighting system in F324, install A60 protection in T331 or move components (Line MSB-Subdistribution station 1 would be lost in case of fire). Consider also the installation of "casualty resistant" material instead of re-routing the line (not preferred solution)"

Even if, as already mentioned, it is not the intention of the tool to suggest which solution, among the possible ones, is better, it has been chosen to indicate that the choice of "casualty resistant" material for lines is not preferred to re-routing the line because there are clear indications from the CS about this design solution. DNV GL for example, defines it as "last resort" solution [10]. It is proposed anyways as it is still a feasible option to achieve the compliance.

10.3. Move components

The "move component" solution is the most common solution proposed and it is often applicable. It is also the only possible solution when components of different subsystems have been installed in the same space. This solution will be proposed in every scenario for which the compliance is not achieved, even if there are some components that are not likely to be moved (e.g engines or other particular components strictly dependent on their position on board as shaft lines). Here is reported an example of how the "move component" solution is proposed, in the assessment for casualties exceeding the threshold:

"If MVZ 1 is lost, both subsystems are affected. There are 3 components of Subsystem A (['Engine 1', 'Generator 1', 'Alternator 1']) and 1 components of Subsystem B (['Generator 2']) not protected. Some components must be moved."

and for casualties within the threshold:

"There are components of both subsystems in the same Watertight compartment W211 (['Generator 1', 'Alternator 1'] of Subsystem A and ['Generator 2'] of Subsystem B). In case of flooding in this space both subsystems would be affected, some components must be moved."

Other than proposing the possibility to move components elsewhere from the compartments affected by the casualty, in the tool has also been implemented a dedicated functionality to suggest the user where the misplaced component can be moved in order to achieve the compliance. It is important to mention that the tool has a significant limitation in proposing the location in which is possible to move the components. Indeed for the assessment of the compliance of a system with the tool, the input includes all and only the spaces in which the components of such system are installed. In other words, the tool knows the existence of just the spaces defined for the assessment and, in fact, is unaware of any other space on board. This is logically a disadvantage in proposing compartments in which the components can be moved, as there likely are many others possible on board that have not been input in the tool. Conversely, the tool has no limitations when it is desired to suggest the compartments in which the components cannot be placed. Indeed the only constraint for which a component could not be placed in a certain compartment is the presence of components of the other subsystem, which has to be input for the assessment of the compliance. Therefore, while the tool is unable to define all the possible locations, it can very accurately define which locations are not acceptable. In the suggestion of possible spaces to move the critical components the tool will then propose which are the possible spaces among the ones defined in the input, and exactly which are not possible. The "Move component" functionality has been developed independently for OEA scenarios and for SRtP scenarios. This was necessary as the purposes of moving the components are very different in each scenarios. In the following paragraphs, the major features of these two functionalities are described.

10.3.1. Move component solution - casualties exceeding the threshold

After the assessment for OEA scenario, when the compliance is not met, the tool will identify a certain MVZ which, if lost, would affect both subsystems. If it is desired to know where it is possible to move the misplaced components, it is necessary to define first which, among the subsystems types installed in the MVZ, is not supposed to be installed there. The only parameter that the tool is able to compute is the number of components of the different subsystems in the same MVZ. If for example, the amount of components of Subsystem A is greater than the amount of components of Subsystem B, the user will be asked if it is preferred to move the components of Subsystem B (Figure 10.1), giving also the possibility to choose to move the components of the other subsystem.

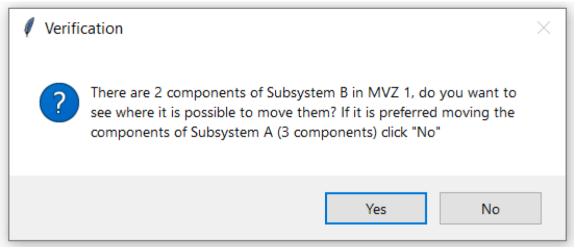

Figure 10.1: Example of verification message - move components functionality OEA scenario

Once the user has chosen the subsystem type that is preferred to move from the MVZ analysed, the tool will search for MVZ dedicated to that subsystem type, where is possible to move the misplaced components. The feasible and unfeasible options are printed in the command prompt. An example of the solution printed is:

"The Main Vertical Zones where it is possible to move the components of subsystem B installed in MVZ 1 are: MVZ 3 MVZ 4 and all the other MVZ different than MVZ [1][2]"

If there are not MVZ with only the selected subsystem type among the ones defined in input, the message shown would be:

"There are not MVZ with elements of Subsystem B only among the ones considered for the assessment of this system (MVZ [1, 2]). It is possible to move the components in any other MVZ or rearrange the disposition of the system within these MVZs."

As it has been explained before, the feasible options are specified to be among the spaces defined and they are also given as exclusion of the spaces in which is not possible to place the components.

10.3.2. Move component solution - casualties within the threshold

The "Move component" solution in the assessment for casualties within the threshold has the goal of suggesting in which compartment is and it is not possible to move the misplaced components. Unlike the functionality for casualties exceeding the threshold, the assessment of the feasible options cannot simply be based on the presence of the other subsystem type in a certain space. Indeed, if a component is placed in an empty local, it can still be affected by a casualty originated in a different space. For this reason the assessment of the feasible options to propose is more complicated with the most detailed space definition. Due to the impossibility of defining *a priori* the acceptable compartments, the only way possible is to re-perform the assessment of the compliance of the system with the position of a component selected among the ones previously mislocated different every time. In this connection, the tool performs the assessment in a loop in which the position of the component changes at every iteration. In this cycle, the component is located every time in a different space among the ones defined in the original input. When an issue with the compliance related to the selected component is found, the position of the component in that iteration is considered an unfeasible option. Otherwise, if no issues with the selected component are reported, the current location will be considered an acceptable option. For this function, a dedicated interface has been developed (Figure 10.2). In the interface it is possible to visualize the components that caused issues with the compliance after the original assessment in a combo box. Thanks to this the user will also be able to select the component for which he wants to perform the assessment of the possible locations. If the same component has been installed in multiple compartments (e.g. a line),

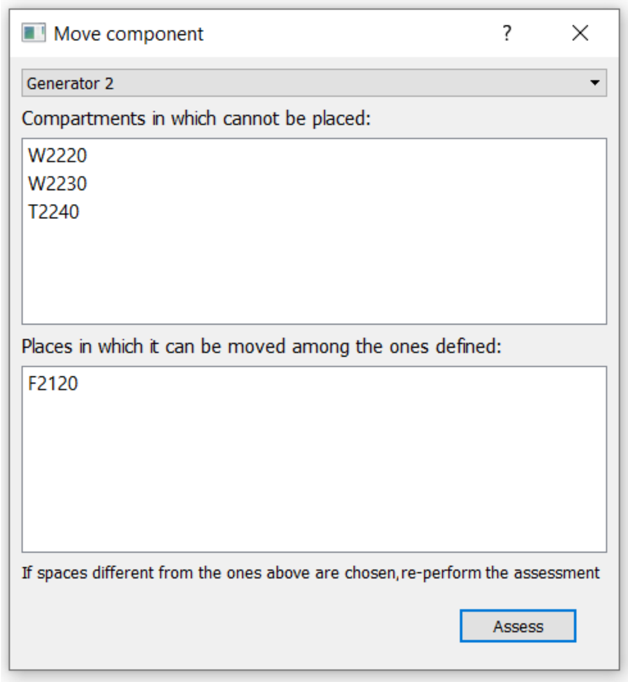

Figure 10.2: Interface "Move component" functionality for casualties within the threshold

the "identification string" of the space for which there was an issue will be visualized next to the name of the component, allowing the user to distinguish the spaces related to the issues (see Figure 10.3). If a component is installed in a place having multiple issues (e.g. a compartment that is affected by a casualty originated in different spaces), it will be notified to the user as shown for "UPS 2" in the figure below.

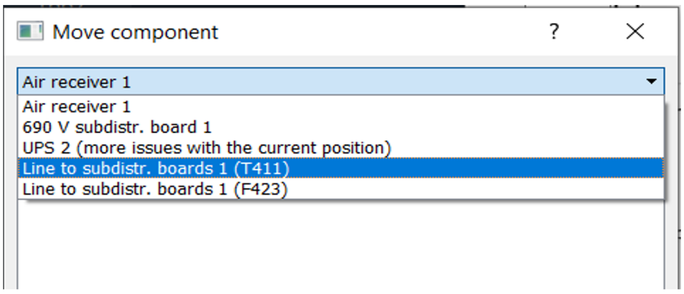

Figure 10.3: Examples of components displayed in combo box - interface "Move component" functionality

After the assessment for the selected component, in the interface will be displayed the list of spaces (among the ones defined), in which is possible to move the component and the ones in which it is not possible. It is important to mention that, unlike the assessment for casualties exceeding the threshold, also the list of spaces in which the component cannot be placed is not complete. There might be in fact, a space among the ones not given as input that can be considered lost in the spreading of a fire casualty. For this reason it is suggested to re-perform the assessment of the compliance if it has been chosen to move the component in a compartment different than the ones defined in input.

11

Testing of the model

The testing phase is an essential step in every project involving a model. There are multiple purposes and goals of this phase and each one of them has to be pursued in the best way possible in order to properly test the model. It is therefore fundamental to set up a well-thought-out testing strategy in order to accurately achieve all the goals of this phase. Due to the wide diversity of these, it is deemed necessary to combine different tests and test types in order to discern and examine all the relevant aspects, facets and features of the model.

11.1. Testing strategy

The testing of the model will be performed in different stages, each one of them having different purposes. The first step is the verification of the model, then the validation of the model will follow. While the verification should answer the question "is the model right?" the validation answers the question "is it the right model?". In fact, the verification of the model is performed to make sure that the implementation of the model is correct, i.e. without mistakes or errors in the code. The validation instead, is necessary to understand if the model is consistent with the intended application and purposes of the tool. Clearly, both phases are essential and must be carried out at the beginning of the testing process. The goal of the testing of the model however, is not limited to the verification of the correctness and of the consistency with the intentions of the tool, but it is also meant to evaluate other parameters. For example, if and how effectively the tool meets the requirements set in the Literature Review. Among the relevant aspects that is desired to determine during the testing of the model there are:

- Effectiveness of the tool in mitigating design risks;
- Actual applicability of the tool, if it would really be utilized by designers at the Company;

- If it can be applied with a correct level of detail and/or diverse levels of detail, if it could be utilized in the early stages and/or different stages of the design process;
- Where in DAMEN's workflow it could be applied;
- Quickness and ease of use;
- If the assumptions made are valid;
- The level of "reusability", if it could be easily applied to different projects;
- Effectiveness in reporting and explaining the type of issue;
- Effectiveness in providing design solutions to meet the compliance;
- If there are improvable aspects/features.

Since there is not an unique way to efficiently perform these assessments, the testing process has been further divided into two steps: a testing phase with the engineers at the company and a case study. The case study is necessary to understand the behaviour of the tool in a real scenario, simulating the conditions in which the tool will actually be applied. With a single or few case studies however, it is not possible to fully judge many of the aspects listed above. To get complete insight into some of the parameters that are intended to be evaluated during the testing phase, it will be necessary to resort to the experience of the engineers at DAMEN. Their feedback and opinions, combined with the personal experience derived from the case study, are deemed the best strategy possible to assess the overall quality of the project. In this chapter Validation phase, Verification and the feedback sessions held with the engineers at DAMEN are described. A separate chapter will instead be dedicated to the case study.

11.2. Verification

As mentioned already, the verification is meant to ensure that the model has been correctly implemented. This type of testing has been performed since the beginning of the project. It is, in fact, an iterative process that takes place throughout the development of the model. To find and fix errors in the implementation of the model, some of the most common strategies for the verification of software models have been applied. Among the most used ones there are:

- Check of variables values;
- Check of variable types;
- Check of elements in lists;
- Counters in the loops;
- Check events orders and casual relations between blocks of code;
- Tracking logic flows.

These strategies have been applied for every block of code written during the development of the software and they also allowed to understand the behaviour of the model. The accurate understanding of how a program works in fact, is arguably the most solid strategy to ensure that the code runs smoothly. Once the complete model has been fully understood and all the possible mistakes found and fixed, the Verification phase is considered concluded.

11.3. Validation

The validation phase is meant to prove that the tool is able to perform the tasks for which it has been designed. To evaluate if the model works as intended, a set of tests covering every scenario that has been implemented in the code have been run. During this phase, a wide range of input data simulating designs deliberately non-compliant with the regulations has been given in input, in order to evaluate if the tool was able to identify the problems and to correctly report them to the user. The testing set up, simplified as much as possible to isolate the issue given in input, consists in two compartments for most of the tests.

In the test scenarios reported in the table in Appendix A , Input 1 represents a compartment containing a component of Subsystem A while Input 2 a compartment with components of Subsystem B. During the tests, the tool has always been able to identify the problem purposely input, even when multiple "elementary" issues were combined. This sort of testing has been performed also for the other functionalities of the tool, namely for the design solutions provided. For the testing of these functionalities the strategy slightly differed from the one described above. Instead of data simulating non-compliant designs, random data was input in the model and the correctness of the results was analysed. However, due to the necessity of scaling up the complexity of the tests to effectively perform the other functions, there was no efficient way to display the tests performed in a table. No evidence of the testing of these functionalities is provided.

After all the tests of the validation phase have been concluded, the performance of the tool has been judged adequate, and the testing process can continue with further analysis.

11.4. Feedback sessions with engineers at DAMEN

To complete the testing process, while the tool was verified, validated and applied to the case study, feedback sessions with the engineers at the Company were organized to hear their opinions about the project. This has been performed with two different approaches. First, several personal meetings with the engineers most involved in the project's topics were arranged, subsequently a collective presentation for all the employees at the office was given. The personal meetings were held to discuss specific topics with the competent people in the subject matter in DAMEN CRO and even outside the branch [1], the joint presentation instead was meant to involve as many people as possible, so to broaden the array of opinions.

The tool was generally welcomed with enthusiasm, as its potential and its possible applications have been promptly recognized. Most of the choices and the solutions implemented in the tool have been substantially appreciated and the assumptions made have been validated. This section however, will focus on the remarks and on the ideas to improve the tool arose during the feedback sessions. First of all, despite the considerable appreciation of the string code created to label the spaces, which turned out to be very useful in diverse design disciplines, it has been pointed out that it might be more intuitive, so to simplify the use of the code for different people in different design activities. Another comment concerned a possible implementation of the drawings of the ship in the model, so to facilitate the input process. However, even if undoubtedly helpful, this option would significantly increase the time required to apply the tool, since additional time to model the ship in the software would be required. Furthermore, the advantages of this feature can be largely achieved by opening the GA of the vessel on a separate window during the input process, although it would not be possible to highlight the potential issues on the drawings, as conceived by a colleague.

Also doubts about the reusablity of the diagrams arose during these sessions, especially concerning different variants of the same system. It has been explained that ideally all the different solutions for each system could eventually be implemented in the tool, covering all the possible scenarios. In this connection, a plain interface used to test the model before the implementation of the systems diagrams for the case study, with only input lines for two generic subsystems, was deemed more reusable and equally useful as the intended tool. The reusability of the systems has then been expressly discussed with a system engineer at the Company, all the considerations about this requirement are reported in Section 13.3.

Among the strengths and the most appreciated features of the tool pointed out in the presentations there are the efficacy in asking details about the relative position of the spaces only if necessary, which is deemed a valid "time-saver" solution, the space definition combining information about passive and active fire fighting systems, very useful data for many design activities, and the idea of labeling the spaces on board according to position and characteristics. Moreover, many ideas for the further development of the tool arose during the meetings. These will be analysed in Section 13.5.

[1] Aleksander Markovich, Naval Architect DAMEN CRO
Luca Codiglia, D&P Engineer Cruise DAMEN CRO
Francisco Valls Cañas D&P Engineer Ro-PAx DAMEN CRO
Aleksi Halinen, System Engineer DAMEN ENGINEERING HELSINKI
Matti Huhtala Senior Naval Architect DAMEN ENGINEERING HELSINKI

12
Case Study

The case study is a fundamental part of the testing process. The purpose of the case study is to analyse the behaviour of the tool in a real application scenario, and to gain personal experience on the applicability of the model.

12.1. General Arrangement plans

For the case study, General Arrangement plans of real projects have been provided by the Company. Ideally, the designs used for the testing should present issues with the compliance with SRtP regulations, in order to assess if the tool is able to correctly report the problems, and also to provide valid and useful design solutions to remedy to the shortcomings in the design. However, even if problems with the compliance with SRtP regulations often occur, they are promptly corrected and no evidence of these is left in the GA archived. For this reason, if a non-compliant design is desired, it will be necessary to "recreate" the problem with the compliance, which is only possible if precise information about the issue is available. About GAs, it also important to mention that the level of detail in the documents provided by the D&P Office at DAMEN varies significantly. While in some GA almost all the components of the major systems are shown, in some others only the arrangement of the space and few other details are reported. In Figure 12.1 two GAs of Ro-pax vessels are displayed as example of the different levels of detail possible in the General Arrangement plans.

Given the different levels of detail in the GAs, it was deemed convenient to apply the tool to the least detailed GA provided, in order to evaluate which is the minimum level of detail required by the tool to be applicable, i.e. how early in the design process can the tool mitigate the risks in the design. However, also testing to what extent can a GA be detailed in order to be tested with the tool was deemed interesting for the sake of the evaluation of the potentiality of the tool. Therefore, it was decided to carry out a second case study with

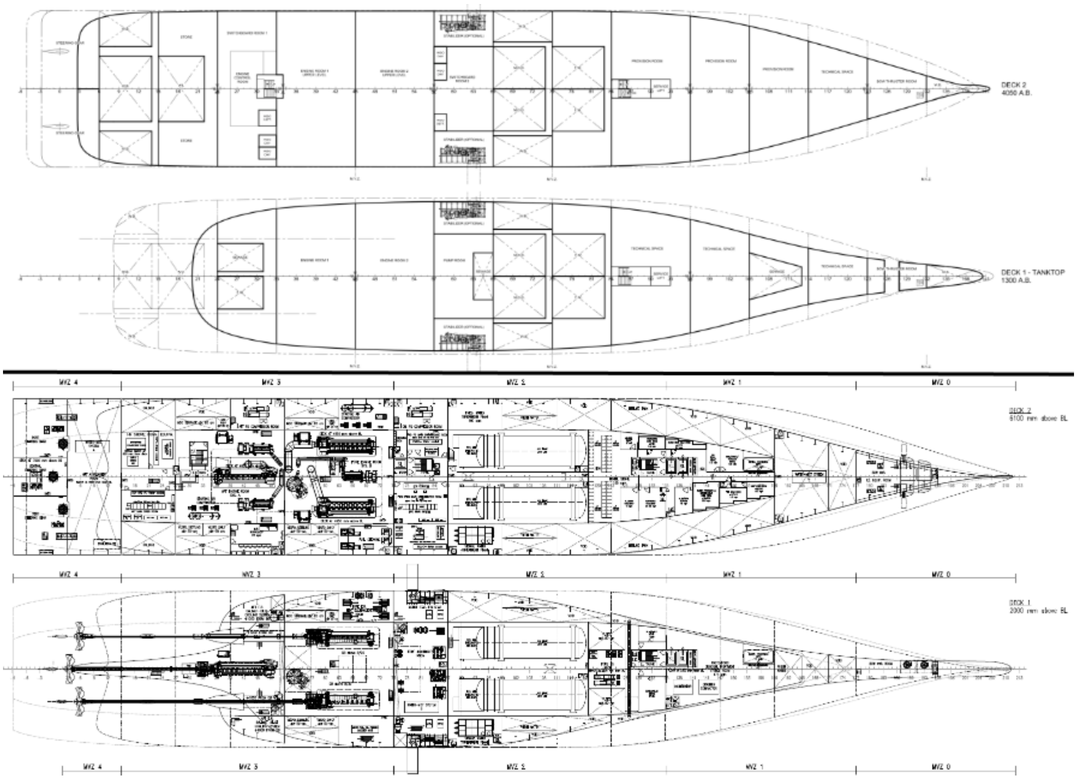

Figure 12.1: GA plans - Top, low detail GA, bottom detailed GA (first two decks, Ro-Pax vessels)

the most detailed GA provided, and by doing so, identifying the range of applicability of the tool. In this second case study, instead of assessing a non-compliant design, the tool will be challenged with the verification of the compliance of the project. The choice of two case studies was deemed the optimal strategy to test the tool covering the most relevant scenarios that will possibly occur: a non-compliant and a compliant design, and a low detail and high detail GA.

12.2. Case study 1: Ro-Pax vessel

The first case study consists in the application of the tool on the General Arrangement plan of a Ro-pax ferry, of course required to be compliant with Safe Return to Port regulations. Due to confidentiality of the project, no further details about the vessel will be disclosed. As mentioned in the paragraph above, this project has been selected to test the applicability of the tool in the earliest stages of the design process. In addition, it was possible to recreate the actual issue related to the compliance with the regulations since it occurred during the internship at the Company, and evidence of it was promptly conserved.

The GA, showing the preliminary drawings of the vessel, was provided to the the D&P office at DAMEN by a third party design company. Once the GA was received, it was checked for potential mistakes and one issue was reported. This is the exact scenario in which the tool is meant to be applied. Its application however, might be limited by the very low level of detail of the design. The purpose of this case study is to analyse how efficiently can the tool mitigate the risks entailed by the regulations in a design with low level of detail. Since the design is in its very first stages, no components and no information about the systems have been implemented in the GA, which only contains information about the division of the main spaces on board. It is however possible to assess the right arrangement of the tanks on board, which is nonetheless an essential procedure in the evaluation of the compliance.

12.2.1. Space division

It has been explained in the previous chapters that the first crucial part in the application of the assessment tool is the definition of the spaces according to the criteria explained in Section 9.1.2. To perform the space definition, all the spaces relevant for the assessment have been identified following the few indication available on the early stage GA. More specifically, all the watertight boundaries and the fire boundaries have been highlighted on the GA, subsequently they have been labelled according the criteria explained in Section 9.2. It is important to mention that trunks are not usually depicted in the General Arrangement plans, even in more detailed design stages. The information about trunks are usually provided in the documents describing the layout of the systems, obviously not available at the design stage of the GA analysed. However, since no information about the systems, and therefore about the routing of the system, are reported, it is not necessary to consider trunks for the assessment of designs at this stage. In Figure 12.2 is shown how the spaces on the GA have been divided and classified in the first two decks of the Ro-Pax ferry. Since no documents such as the Fire Integrity plan or the equivalent document describing the arrangement of the watertight compartments are available in the early stages, the division and the classification of the spaces have been performed combining the few information available on the GA and the experience of the engineers at the Company. Obviously for a skilled engineer defining where are the watertight or fire boundaries on a GA is not a difficult task, especially in the first stages of the design process when the compartmentation of the ship is still basic. Some other information, like the installation of active fire extinguishing system, is derived from other regulations, which for example require the installation of a FFF system in the engine rooms. It is important to mention that different boundaries types coincide or overlap with each others. It is essential to take this in mind at the moment of the evaluation with the tool according to the assumptions made in Section 9.1.3.

12.2.2. Assessment of the design

As previously mentioned, the assessment that will be performed at this stage is on the arrangement of the tanks and, more specifically, on the tanks of the Fuel Oil System. For this purpose, a diagram of the Fuel Oil system is drafted and implemented as interface of the tool. In Figure 12.3 the diagram of the Fuel Oil system is shown.

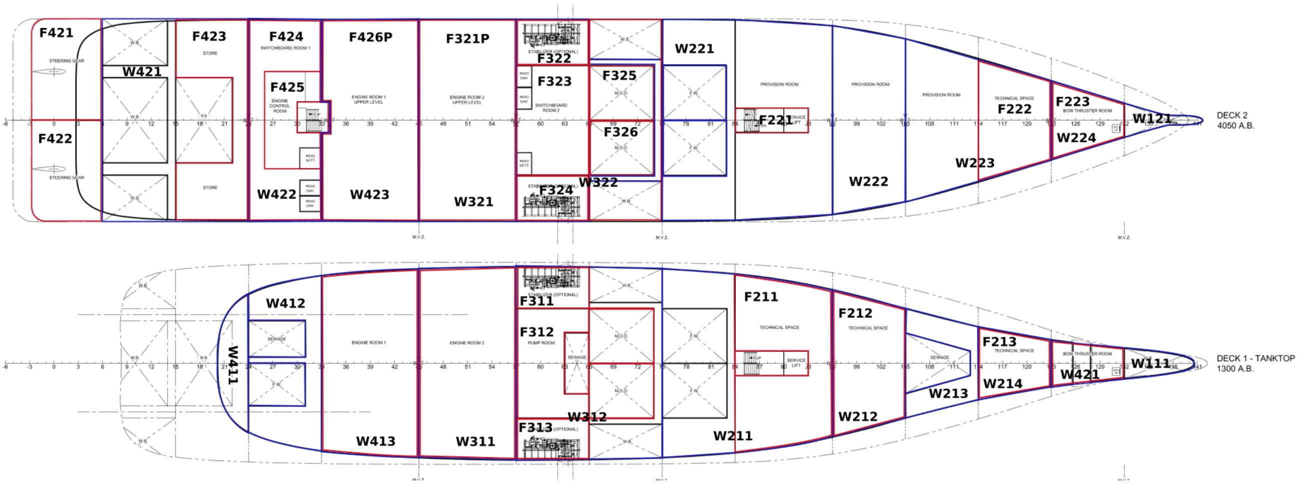

Figure 12.2: Division of the ship in spaces - Ro-pax vessel, case study 1

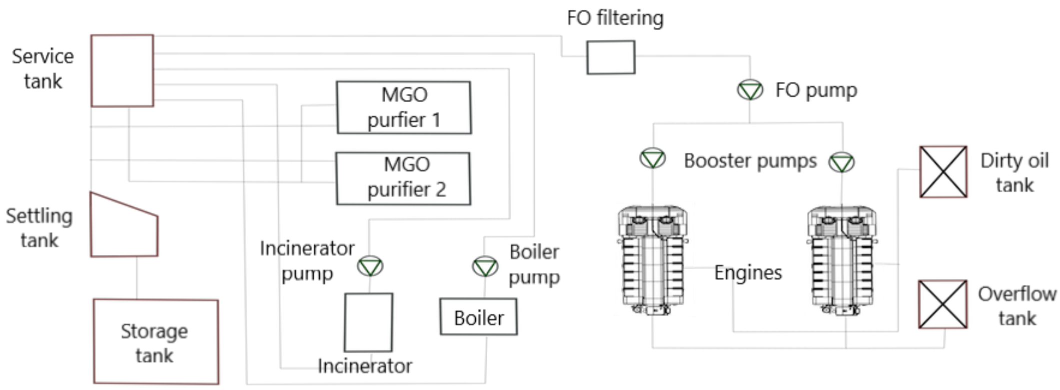

Figure 12.3: Outline of Fuel Oil system

The Fuel Oil system belongs to the first family of systems (see Section 8.2) and it has the purpose of supplying the fuel to the engines. The system is usually further divided into three systems; Fuel Transfer system, Fuel Purification system and Fuel Service system. The Fuel Transfer systems transfers the fuel from the storage tanks to the settling and service tanks, the Fuel Purification system removes the impurities in the fuel by means of centrifugal separators (at least one FO Purifier for each engine room), while the Fuel Service systems supplies the purified fuel stored in the service tanks to the diesel engines, incinerators and boilers.

Obviously not all the components depicted in Figure 12.3 are defined at the current status of the design. However, the tool has been designed in such a way that is possible to assess the position of just some of the components of a system implemented in the software, namely only the ones defined at each stage of the design process. This feature enhances significantly the potentiality of the tool, and makes it suitable to many different levels of detail. Once the compartments to be analysed have been categorised and labelled during the space definition and the components of the Fuel Oil system to be evaluated have been identified on the GA, the actual assessment with the tool has been carried out by inputting the position of the components in the software.

12.2.3. Results of the assessment

The system has been tested for casualties exceeding the threshold since it must remain operational as a consequence of the required availability of a source of power in OEA scenarios. Indeed the Power Generation system directly relies on the Fuel Oil system. As expected, the design resulted to be non-compliant with Safe Return to Port regulations. The storage tanks for fuel oil are in fact located in two adjacent Fire boundaries (F325,F326) in the same MVZ (MVZ 3). Below the output of the evaluation:

If MVZ 3 is lost, both subsystems are affected. There are 1 components of Subsystem A (['Storage tank 1']) and 1 components of Subsystem B (['Storage tank 2']) not protected. Some components must be moved.

Furthermore, after the implementation of the propulsion system in the tool for the second case study, the model has been re-tested to complete assess the information available on the General Arrangement plan. In this connection, after the assessment of the spaces dedicated to the propulsion system for casualties within the threshold, another issue with the compliance was reported. It resulted in fact, that the arrangement of the spaces for steering and propulsion (F421 and F422) does not guarantee at least one azimuth thruster to remain operational in case of casualty. Indeed, being the two compartments adjacent and not provided with fixed fire-fighting system, any casualty originated in one of the two compartments would cause the complete failure of the propulsion system. The solution proposed by the tool is to install an active fire extinguishing system in both compartments, in order to alter the extent of the casualty and, in so doing, achieving the compliance with the regulations. The issue reported by the tool is:

Install fixed fire fighting system in F421, a fire casualty could spread into F422 where there are components of a different subsystem. Alternatively move critical components. The fire could also spread from F422 to F421 since they are adjacent. Install fixed fire fighting system in both compartments.

The tool also proposed the "move component" solution which is clearly not applicable as the position of the two components is strictly fixed. The accuracy in the suggestion of the solutions in this case could be easily improved, for example by implementing in the software position constraints for some components like the ones in question. For the wrong arrangement of the tanks instead, the "move component" solution was the only pertinent, since the storage tank of Subsystem B has to be moved to a different Main Vertical Zone. When asked a new position for the misplaced tank through the "Move MZV" functionality of the tool, it suggested MVZ 4 as the feasible option among the ones considered for the assessment and all the MVZ different from MVZ 3.

The Main Vertical Zones where it is possible to move the components of subsystem B installed in MVZ 3 are: MVZ 4 and all the other MVZ different than MVZ [3]

In the emended GA, the storage tank for Subsystem B was moved to MVZ 4, where a FW tank was rearranged as fuel storage. Regarding the issue of the propulsion room instead, in addition to the installation of fixed fire-fighting system, it was also suggested the option of separating the two compartments by introducing another fire boundary in between. By doing so, whatever casualty originated in one of the two propulsion rooms without FFF, would be considered to spread up to the nearest A0 boundary, which would be the added compartment. This solution has not been considered during the development of the software but it might be a valuable design solution to achieve the compliance with lower costs than with the installation of an expensive active fire extinguishing system. However, since this solution is not always applicable and in some cases even not advisable (e.g. the alterations of watertight boundaries might cause major stability issues), the limitations of this solution have to be thoroughly studied before considering a possible implementation in the tool. In the emended version of the GA of the vessel in question, the additional fire boundary in between of the propulsion rooms is not present and also no information about the installation of FFF is available, therefore is not known which solution has eventually been selected. To conclude, the tool was deemed effective in the mitigation of the risks of non compliant design and capable to deal with the low level of detail. Furthermore, it was able to suggest valuable design solutions to achieve the compliance, even if the accuracy in the provision of the solutions can be improved. Additional solutions might be implemented after a complete analysis of the possible effects.

12.3. Case study 2: Expedition cruise

The second project to which the tool was applied is an expedition cruise with an overall length of nearly 164 meters. As in the first case study, no other details about the vessel will be disclosed due to the confidentiality of the project. The design of the cruise has been developed till the end of the Fixed&Firm phase (see Chapter 4), therefore the project reached a significant level of detail. All the systems and their components have been designed and located on board. The purpose of this second case study is verifying the compliance of the Power Generation and Propulsion system of the vessel in question. It is important to mention however, that for a correct assessment of the compliance of whatever system, it is necessary to verify also the compliance of all its auxiliary systems and the other system on which it is dependent. Indeed if this analysis is not performed, it is not possible to assure the correct operation of the system in case of any casualty. In this connection, the Power Generation system, according to the Company's document describing the structure and the philosophy of the system, relies directly on the functionality of the following systems:

- Power Distribution;
- Fresh Water Cooling System;
- Sea Water Cooling System;
- Compressed Air System;
- Fuel Oil System;
- Lubrication Oil System;
- Exhaust Gas System;
- Machinery Ventilation;
- IAMCS.

Obviously the assessment of these systems in the case study is limited to the analysis of duplicated systems, as only the software for the first category of systems has been developed for the thesis project. Surprisingly enough, almost the totality of the systems on which the power generation is dependant, can be considered duplicated systems and therefore they could be assessed by means of the tool. Even if some systems in facts, belong to the second category, such as the power distribution system, they have been designed as duplicated systems to support the power generation with the same level of redundancy. Therefore, where duplicated, they have been implemented in the tool, allowing a complete assessment of power generation and the propulsion. The only system that has not been considered is the IAMCS (Integrated Alarm Monitoring and Control System), as it is essentially composed of only the engine control cabinet as physical component, which is assumed to be included in the generator set.

12.3.1. Space definition

As in the previous case study, the first step in the evaluation of the compliance of the systems is the definition of the spaces on board. With a greater level of detail however, this operation is obviously more laborious. To correctly identify the casualty boundaries with the high compartmentation of the project it was necessary to resort to the Fire integrity plan as well as the Tank Arrangement plan for the description of the watertight boundaries. Following the identification and categorization of the compartments on board, each space has then been labelled according to the criteria required by the software. In Figure 12.4 the space definition is reported. The division is limited to the first four decks of the cruise ship. Information about trunks is not available on the GA, despite the high level of detail. This kind of information was derived from the documents describing the structure of the systems. Furthermore, also information about the installation of active fire extinguishing system is not reported in the GA nor in the Fire integrity plan. Therefore it has been decided to consider every space lacking of such protection except for the compartments in which is required by other regulations (engine rooms). The space identification and categorization of a GA with high compartmentation and considerable level of detail was deemed a laborious procedure overall. It is important to mention however, that this task could be significantly simplified if the space definition was performed since the early stages of the process and subsequently carried on during the development of the project, implementing and elaborating the new information and details available at each stage instead of processing them all at once.

12.3.2. Assessment of the systems

Once the space definition has been completed, the information to input in the tool for the assessment of the systems is available. As already mentioned, all the systems on which the Power Generation system and therefore the Propulsion rely, have to be assessed at the same time in order to verify the availability of these systems in casualty scenarios. However, while the propulsion system has to remain operational only in case of casualties within the threshold, the power generation and its auxiliary systems must withstand a casualty exceeding the threshold (i.e. a whole MVZ lost). This is particularly important to take in mind during the assessment of the systems. Since they all have been implemented in the same software and an independent assessment for different extent of casualty has not yet been implemented in the tool, they will be assess separately. Since systems compliant with OEA scenario also comply with SRtP scenario but it is not true the opposite, first will be input the components to be assessed for casualties exceeding the threshold and subsequently all the other components to be tested in SRtP scenario. The structure and layout of the Propulsion, Power Generation and all its auxiliary systems will be reported in this section.

Power Generation, Power Distribution and Propulsion systems

The power generation system supplies the power on board. Since it provides electric power to all the systems, it is required to remain operational in every casualty scenario. Each electrical power plant has its own diesel engine, alternator, engine control cabinet and other equipment necessary for the correct operation of the engines and generators, which power their respectively Main Switchboards (MSB). All the power distribution equipment and auxiliary systems required for the operation of the power plant are duplicated in order to be able to operate independently of each other. The power distribution system is built to distribute the electrical power from generators and battery systems to the electrical consumers. It consists of 690V main power distribution system, 230V and 120V main power distribution system and 230V UPS (Uninterruptible Power Supply). Power distribution system is also required to remain operational in OEA scenario. The propulsion system, electrical with azimuth thrusters in the project analysed, is instead required to remain operational just for casualties within the threshold. Each azimuth thruster is considered to have the sufficient power to produce required propulsion during SRtP voyage in the prescribed conditions (6kn in Beaufort 8). In the expedition cruise of the case study, azimuth thruster (F541) is supplied from 690V MSB in MVZ 3 (F335) and azimuth thruster 2 (F543) is supplied from 690V MSB in MVZ 4 (F4315). Figure 12.5 illustrates the interface of the tool used for the assessment of the power generation, distribution and propulsion system. In the interface it is possible to notice the diagrams drawn for the systems in question. In ad-

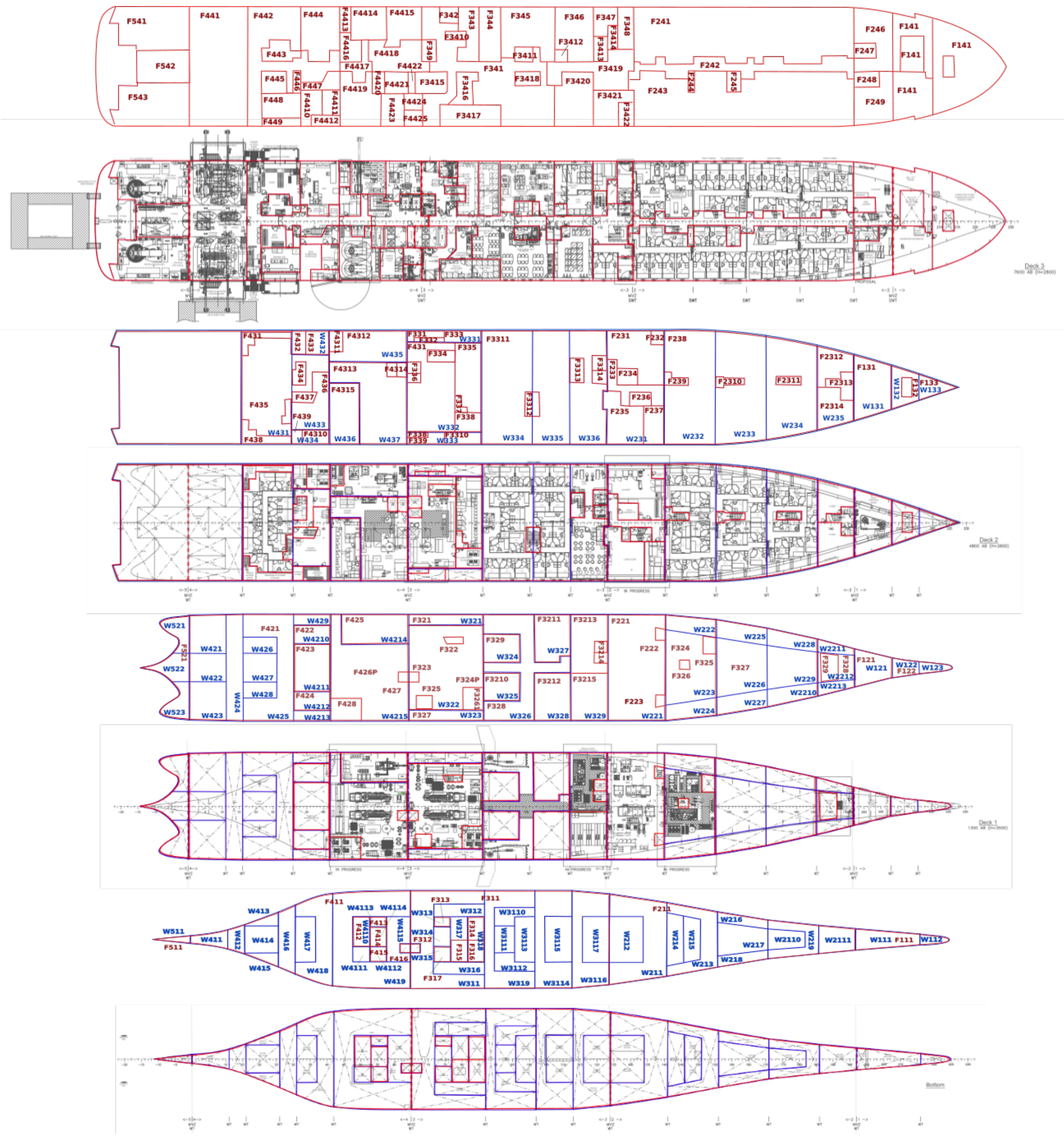

Figure 12.4: Space division expedition cruise

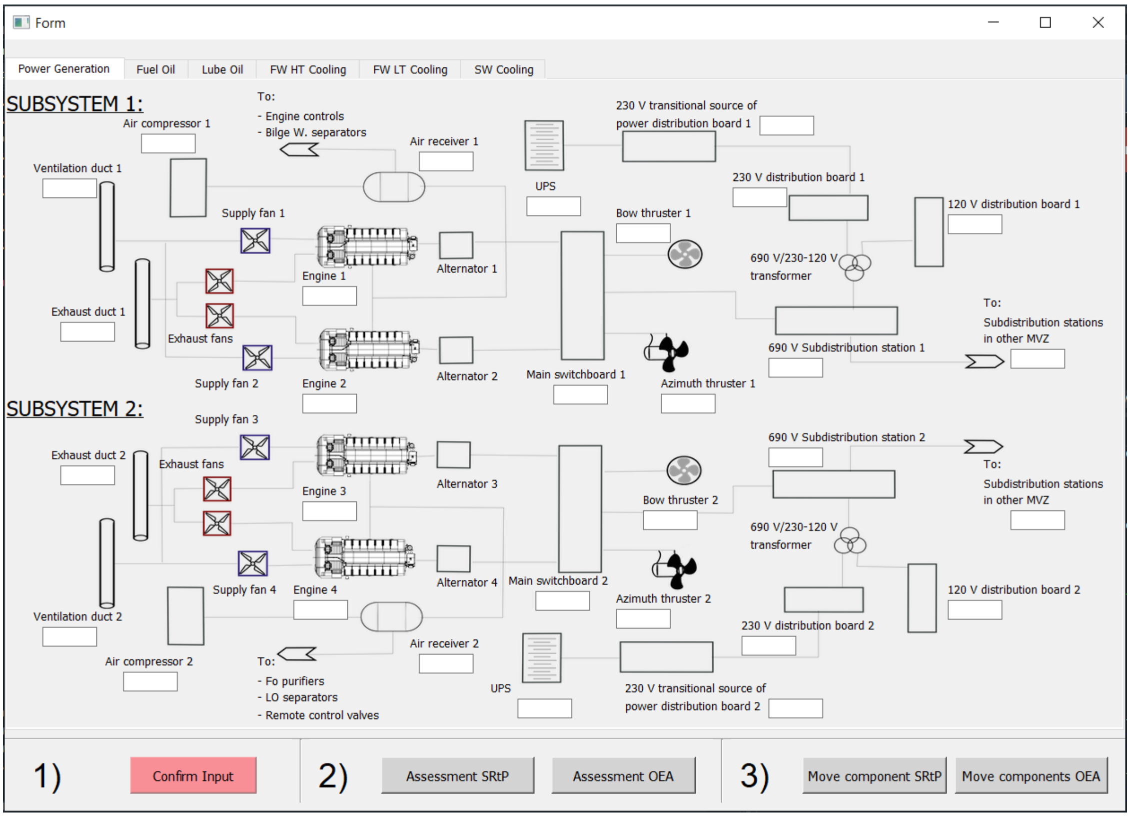

Figure 12.5: Interface for the assessment of Power Generation, Power Distribution and Propulsion systems

dition also components of machinery ventilation, exhaust gas and compressed air systems have been included in the same diagram, since a different dedicated interface was deemed not necessary. In the project analysed, each engine is provided with an individual exhaust duct routed via funnel outside. There are two independent funnels where the exhaust pipes are located each for one ER. The ventilation system instead consists of two ventilation fans (one supply, one exhaust) for each engine room. In the expedition cruise these systems are physically separated, including ducting, and located in the respective ERs.

Fuel Oil system

The brief description of the system was reported in Section 12.2.2. Indeed the same diagram and the same interface has been applied to both case studies. This can efficiently prove the reusability of the diagrams, applicable in different projects and even with very different levels of detail. In Figure 12.6, the interface illustrating the two subsystems of the Fuel Oil system is reported.

Lube Oil system

The Power generation system depends directly on Lube Oil systems as it is fundamental to grant the correct operations of the mechanical components. For this reason, it is required to remain operational in OEA scenario. Being a duplicated system, each engine is provided with its own individual LO system. As in the case of the Fuel Oil system, particularly attention has to be given in the assessment of the different tanks composing the system, which

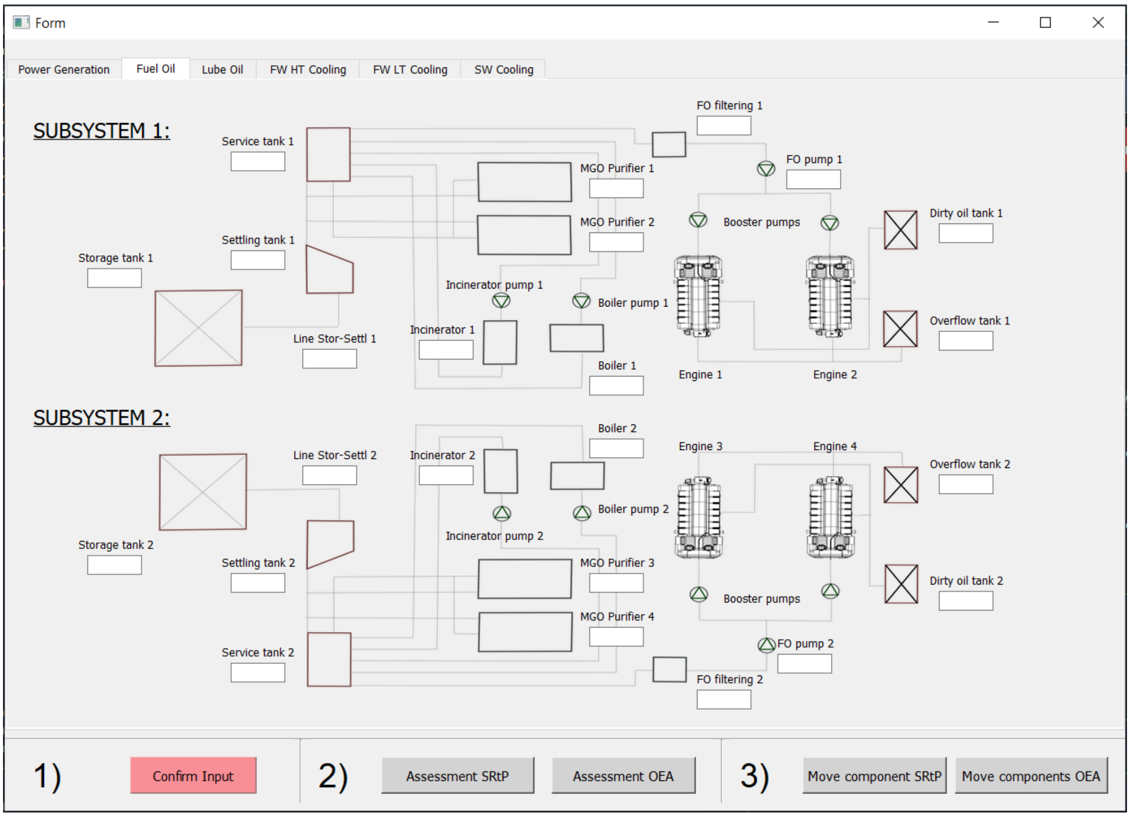

Figure 12.6: Interface for the assessment of Fuel Oil system

are usually placed in different spaces than the engine rooms. The Lube Oil is also an essential auxiliary system for the propulsion equipment. Each azimuth thruster is provided with its own individual LO system, often including additional storage tanks. Since the propulsion system is not required to remain operational for casualties exceeding the threshold, also the components of the Lube Oil system serving the propulsion machinery is to be assessed with the same level of survivability. In the expedition cruise considered for the case study, the tanks are placed in the double bottom while the storing tanks have been placed in the engine rooms, each one serving the respective subsystem. As explained above, the components serving the azimuth thrusters have been input only in the assessment for casualties within the threshold. In Figure 12.7 is reported the interface of the tool illustrating the diagram of the duplicated Lube Oil system used in the second case study.

FW and SW Cooling system

Power generation directly depends on the Fresh Water Cooling systems and, indirectly, on Sea Water Cooling system. The FW cooling system is composed by the Low Temperature FW Cooling system and the High Temperature FW Cooling system. The Fresh Water and Sea Water cooling systems are built with the same level of redundancy as the power generation system. Each of the ERs has dedicated, independent and separated FW and SW cooling systems. The components of the cooling systems serving the Power Generation system are required to remain operational in casualty scenarios exceeding the threshold while the components of the the Low Temperature Fresh Water Cooling system serving the Propul-

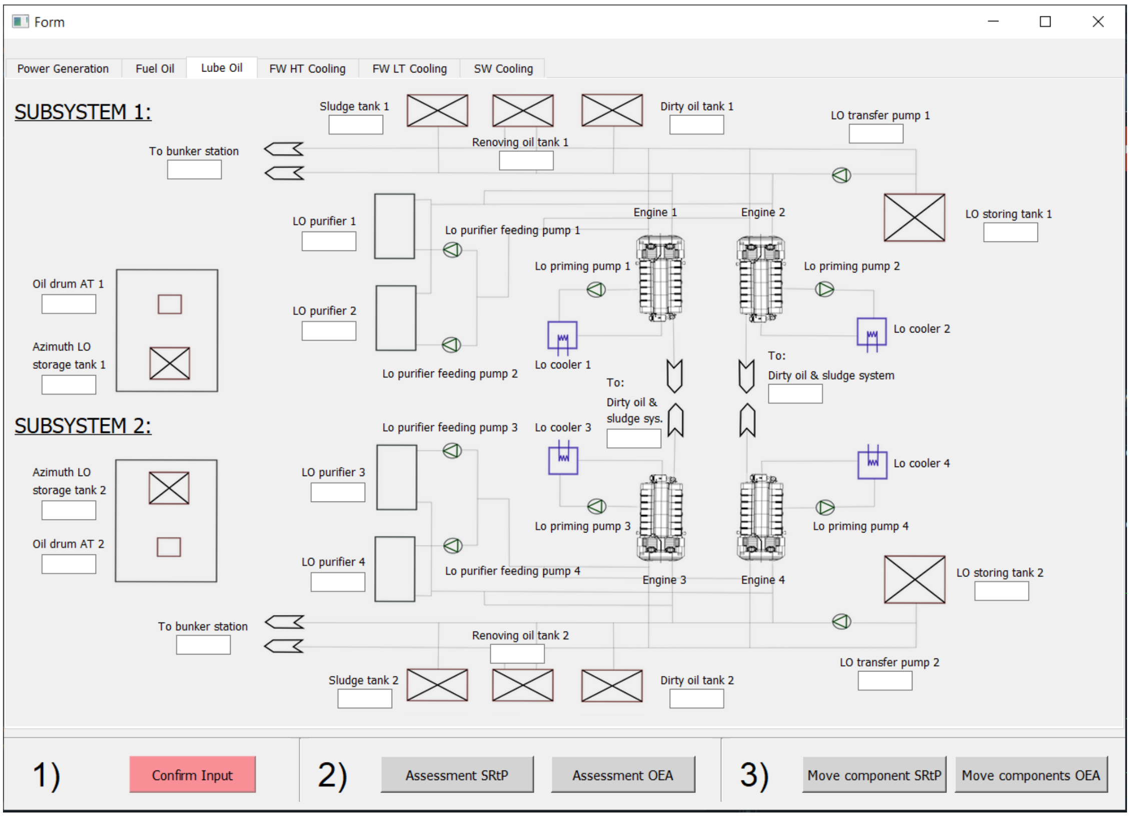

Figure 12.7: Interface for the assessment of Lube Oil system

sion system have been assessed only for the SRtP scenario. Three separate diagrams, and therefore three interfaces, have been created for the assessment of these auxiliary systems. Figures 12.8, 12.9 and 12.10 illustrate the outline of the systems.

12.3.3. Results of the assessment

After the evaluation of the systems according to their required level of survivability, the propulsion functionality was judged to remain operational in every casualty scenario within the threshold while the generation and distribution of power is concluded to remain available even for casualties exceeding the threshold. Even if was not tested the effectiveness of the tool in finding issues in the compliance in the design of the expedition cruise, this case study was extremely useful to understand the applicability and the behaviour of the tool. First of all, the space definition procedure was challenged with a design with great compartmentation and high level of detail. Despite the laborious work, the categorization of the space was deemed suitable for the assessment of a detailed GA without further rules or assumptions. Similarly to the first case study, in many areas different casualty boundaries overlapped or coincided, causing the input process to be longer due to the necessity of indicating all the boundaries.

The level of detail diagrams was deemed appropriate for the assessment of the systems. The position of the main components has been efficiently assessed and where information

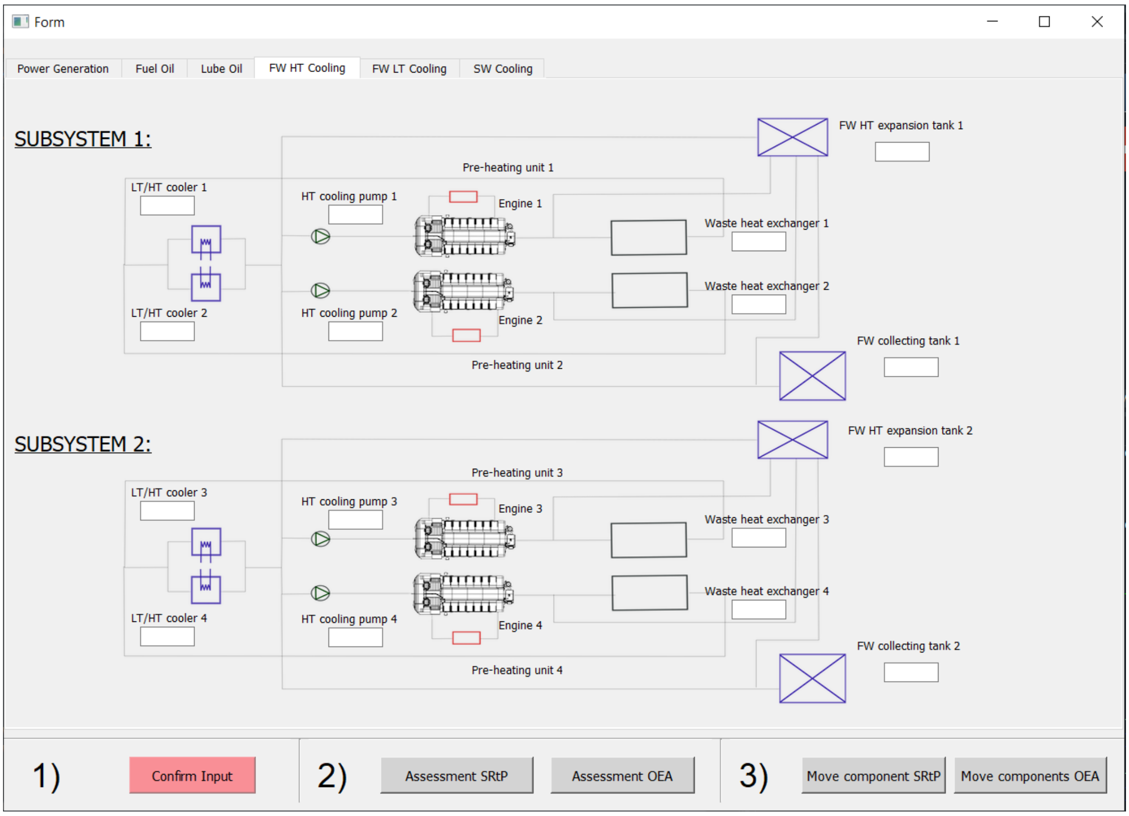

Figure 12.8: Interface for the assessment of High Temperature Fresh Water Cooling system

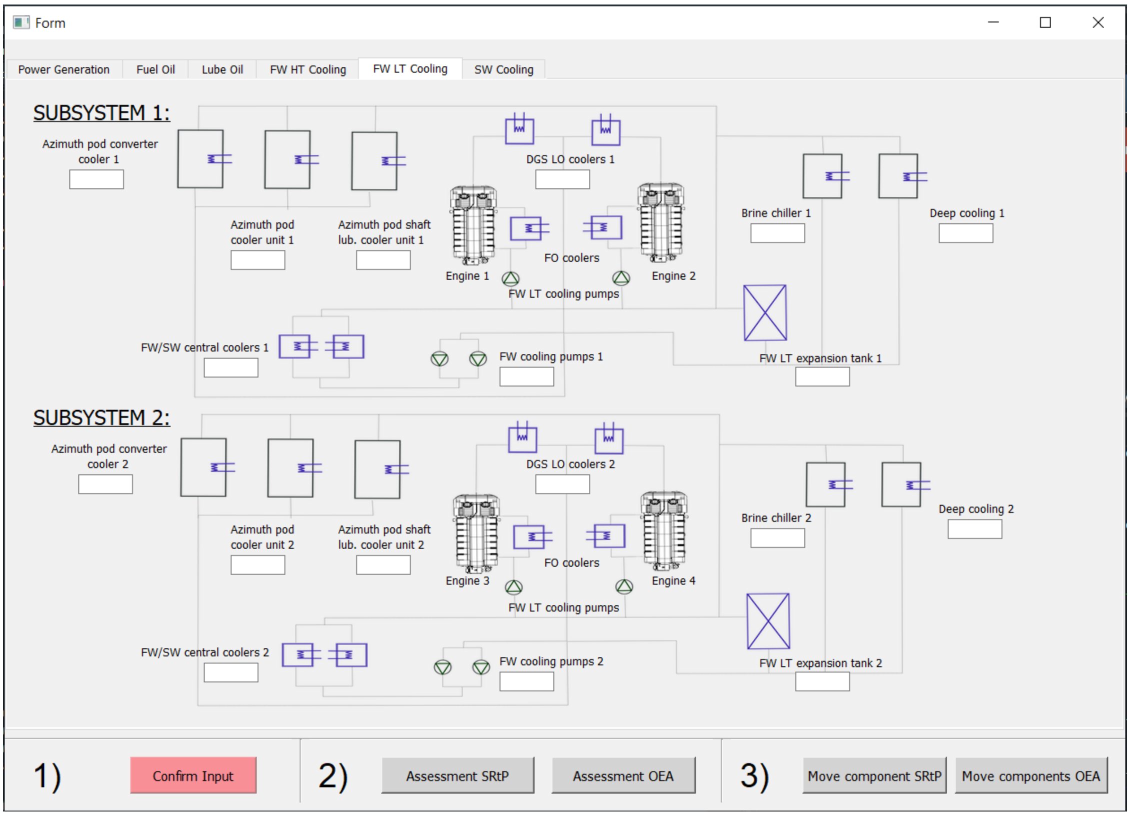

Figure 12.9: Interface for the assessment of Low Temperature Fresh Water Cooling system

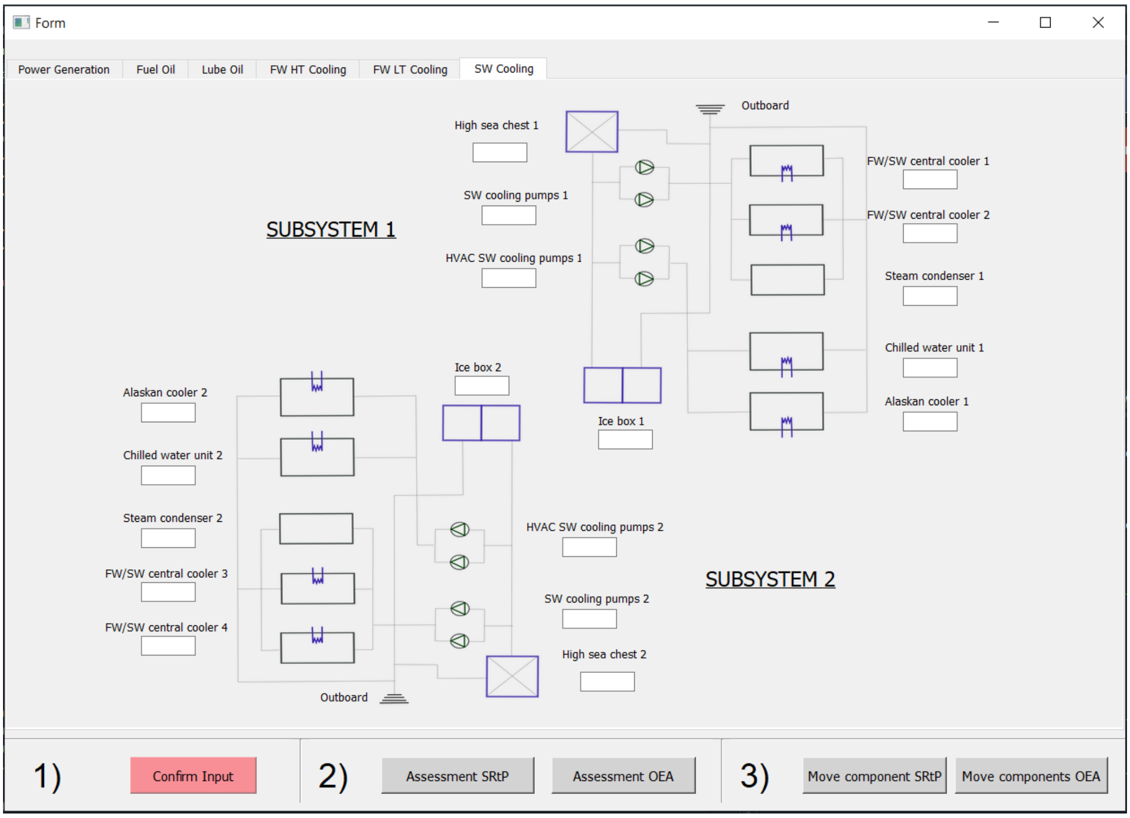

Figure 12.10: Interface for the assessment of Sea Water Cooling system

about some details, like routings or lines, was not available, it has been neglected. In general, if a greater level of detail in the assessment of the system is desired, for example with the implementation of minor equipment such as valves or redundant lines in the diagram, it can be theoretically achieved. Indeed the level of detail in the diagrams is not limited by the tool in any way. Also the time required by the tool to process the data was extremely short, despite the large amount of components analysed, once again proving that the tool could handle even more detailed diagrams. All in all, the assessment of the Propulsion and Power Generation systems, together with their auxiliary system, has been a quite complex and rather long process. This is justifiable if few different factors are taken into account. First of all, the application of the tool on a such detailed and developed design was surely an ambitious goal. Great support in this connection was provided by the simplicity of the tool and its intuitive structure, which makes it user-friendly since the very first applications. Moreover, if the design had been tested since earlier stages, the burden of the testing would have been significantly reduced, for example by just updating the information about the space definition instead of setting it up from scratch, or by knowing already the location of the major components.

Another critical aspect that made this case study harder than expected was the lack of experience in the disciplines involved. Clearly a skilled engineer will not find difficulties in the evaluation of the spaces in the GA or in the analysis of the complex systems installed on board. Therefore it is believed that the effort in the assessment was due to external and personal factors, not to the weakness of the tool itself. Instead, it is deemed an helpful aid in the assessment of the compliance of the systems, arguably a much longer procedure without its support. Concluding, the tool is judged to be capable to handle the high level of detail of this case study and also very useful in the confirmation of the compliance.

12.4. Final considerations on the case studies

After the application of the tool in both case studies, the tool is deemed suitable for the low level of detail of the design of the Ro-pax vessel as well as capable to deal with the high level of detail of the expedition cruise project. The tool was able to report the issues with the compliance of the system in the first case study, effectively mitigating the risks in the design, and even to suggest valuable solutions for the achievement of the compliance. In the second case study the tool turned out to be a considerable support in the verification of the compliance, dealing efficiently with the high level of detail of the project. Thanks to the case studies also some improvable aspects were found, such as the convenience of a new space type. Even if the current space types defined allow a correct assessment of the systems, the introduction of a new casualty boundary combining watertight and fire boundaries would significantly speed the input process up. Moreover, also a functionality to test parts of the same system for different extents of casualties could be implemented to further simplify the assessment process.

During the first case study it was also possible to test the effectiveness of some of the solutions proposed by the tool in a real scenario. Position constraints for some components can be implemented to enhance the accuracy in the provision of the solutions. Also, even the range of solutions can be widened, although following a thorough analysis of the limitations of the options considered. Many other ideas for the further development of the tool arose during the case studies. They will be reported in a dedicated section in the following chapters.

13
Conclusions

In this Chapter will be drawn the conclusions of the thesis project. First, it will be discussed whether the research questions have been answered throughout the report, then the actual value of the tool will be examined. More specifically, it will be debated how efficiently the tool created meets the requirements set during the literature review. Strengths and weaknesses of the tool will also be reviewed.

13.1. Research questions

The research goal was set at the beginning of the project and some research questions were asked in order to guide the research towards the goal. The first question asked was *"what is the Safe Return to Port regulatory framework"*. Clearly a perfect understanding of the regulatory framework was necessary in order to learn how to overcome the challenges set by these regulations. First, the background of the cruise ship regulations has been described by reporting the safety risks connected to this branch of the maritime industry, answering the question *"why was it necessary"* in Chapter 2. In the same chapter, also the innovations introduced with the implementation of the SRtP framework are examined. In the first part of Chapter 3, a thorough analysis of the regulations answers the questions about the intentions, goals and concepts of Safe Return to Port. Section 3.5.1 answers the question *"what are the consequences of their implementation"*, describing the impact of the regulations on the design of the vessels, on the shipbuilding industry as well as on the operations of the ships. The question about similar safety strategies in other industries is answered in Section 3.6, where safety approaches in different industries were studied to find similarities with the concepts introduced with SRtP regulations.

In the second part of the literature review, the design process for ships was analysed. First, the generic design process was examined, then the design procedure for SRtP vessels and finally the design approaches of the Company. Section 4.1 describes the general design process according to literature and Section 4.2 answers the research question *"what are the risks in the design process"*. Several papers on SRtP topics and the guidance notes of most of the Classification Societies have then been studied to describe the design process specific for SRtP projects. This is reported in Section 4.3 where also the challenges in this kind of projects are examined, answering the respective sub-question. Finally, sharing the knowledge gained by interviewing the colleagues at the Company, the design process in DAMEN was thoroughly analysed, to understand at which stage is convenient to mitigate the risks entailed by SRtP regulations.

In the last chapters of the literature review it was concluded that, to mitigate the design risks entailed by Safe Return to Port regulations, a tool to check the compliance of the designs was necessary, answering the research questions on how the risks could be mitigated and what is the best method to do it. In addition, the most complex aspect in verifying the compliance has been identified in the assessment of the systems. In order to be very effective in the mitigation, it was concluded that this has to be performed as early as possible in the design process and that there are no tools for this purpose suitable for the early stages in the market nor in literature. Therefore, after the identification of a gap in the research, the idea of the goal tool has been drafted after the analysis of possible methods applicable to the problem. Then, the requirements of such a tool were set, answering the respective research question. Lastly, an optimal testing strategy has been created, covering the last research question on how the method could be validated. The testing strategy is described in Section 11.1. In conclusions, all the research questions and sub-questions have been answered throughout the report. This allowed to have a complete understanding of the subject, essential prerequisite for the development of a valuable method.

13.2. Research goal

The goal of the thesis was to set up a method to mitigate the risks in the design process entailed by Safe Return to Port regulations. The method developed consists in the definition of the spaces of the ship and the application of the software tool. According to Abbott McKenney, a design tool is, in fact, part of a method and must support it by providing design information [39]. In this case, the tool provides information about the compliance of the systems, essential for the mitigation of the design risks by means of the method. The method has the ultimate goal of preventing re-designs of the vessel costing valuable time and money, and it is considered achieved. As it has been demonstrated in the case studies, the tool is able to identify the non compliant design solutions of the systems installed on board since the earliest stages of the process, effectively mitigating the risk of re-designs. Furthermore, the assessment of the compliance with this method is deemed more time-efficient than the assessment performed without tools, allowing the users to save valuable time, even in case of compliant designs.

13.3. Requirements

During a long and thorough test phase, including case studies and review sessions with several engineers at the Company, it was possible to have enough insight into the project to be able to finally assess its value. In this section will be discussed how effectively the tool meets the requirements set during the literature review. Requirement by requirement, considerations on the tool will be drawn, combining the experience gained in the case studies and the knowledge of the engineers at DAMEN.

13.3.1. Essential requirements

In this section the requirements defined "essential" during the literature review are discussed. As the name suggests, they are considered of paramount importance for the successful achievement of the goal of the thesis.

Ability to assess the design

The ability of the tool to assess the design has been tested during the case studies. However, also personal opinions of the engineers at the Company have been considered in order to have the most complete overview possible. All in all, the tool is deemed capable to assess the compliance of the systems and the spaces of SRtP projects. In the case studies, the tool has been successfully applied to different designs, namely different vessel types (ro-pax vessel and cruise ship) and even different levels of detail (basic design and high detailed design). In the first case study it was able to correctly report the issues in the project, while in the second case study it has been capable to confirm the compliance of the design, proving that the tool has the ability of assessing designs. Moreover, also the opinion of the engineers at the Company was asked in this regard. The tool was once again deemed capable of assessing the compliance of the design and even judged an useful support in the design process.

Sufficient computational power

Concerning the computational power, the tool is deemed to hardly have any limitation. Obviously is not simple to assess the computational power of the software developed as no specific test has been run for this purpose. However, during the second case study the tool has been challenged with a considerable amount of components and it completed the assessment effortlessly (less than a second). Therefore the tool is considered to be sufficiently powerful to adequately accomplish the assignments for which it has been designed.

Low level of detail

In the first case study, the tool has been tested on the design with the lowest level of detail among the GAs provided by the company. With the positive result of the case study, the tool is judged to fully meet this requirement. In addition, the tool has proven to be applicable to a wide range of detail levels. Indeed, the project of the second case study, carried on till the end of the Fixed&Firm phase, is even beyond the required range of applicability set in the literature review (see Figure 5.1). In Figure 13.1 the alleged range of applicability is illustrated on top of Figure 5.1. Indeed the tool is deemed capable to deal also with very detailed designs, only limited by the level of detail of the diagrams of the systems implemented in the software. However, since as explained above, the software has a significant computational power, the level of detail can also be increased as much as desired by the user, potentially overlapping with the level of detail required by the existing tools in the market. The only limitation on the level of detail in the diagrams, and consequently on the level of detail to which the tool can be applied, consists in the reusability of the tool, another crucial requirement which will be discussed hereinafter.

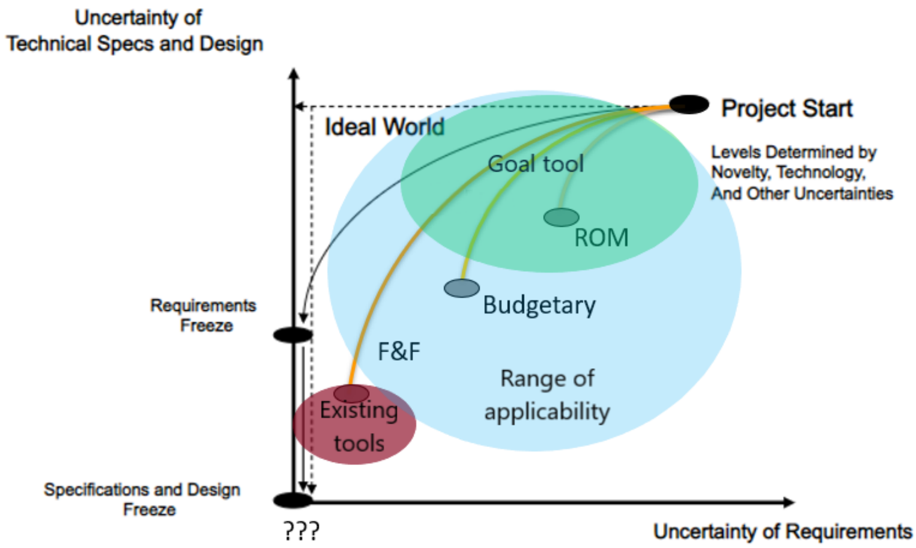

Figure 13.1: Area of applicability (within the design process) of the created tool. In green required range of applicability, in blue actual range of applicability

Reusability

As it has been mentioned in the paragraph above, the reusability of the tool directly depends on the diagrams of the systems implemented in the software. Indeed to assess the reusability of the tool, it is necessary to understand how reusable are the diagrams in the interface. If the same diagram of a certain system works for several projects, then the reusability can be deemed adequate. With the case studies it was possible to have some insight in the matter, but to have a full comprehension of the reusability it has been necessary to resort to the opinion of the system engineers at DAMEN. In the case studies, the same diagram (Fuel Oil system and partially Propulsion system) has been used for both projects, even with very different levels of detail. In this connection, allowing the user to input just part of the components depicted in the diagrams improves significantly the reusability of the tool. It may then be claimed, that a high detailed diagram would make the tool very reusable, as it would make possible assessing all the previous design stages of the system. However, it emerged during the feedback sessions with the system engineers that the more detail is implemented in the diagrams of the systems, the less generic they become and therefore, less reusable. In other words, if a very high detailed diagram is desired is important to take in mind that it will not probably be used for other projects, unless the same design solutions will be undertaken. On the other hand, it could still be a valuable idea developing and implementing high detailed diagrams specifically for a project, in order to test the compliance of the system from the very first design stages to the most advanced ones. Another consideration on the reusability of the diagrams of the systems discussed with the system engineers is that the diagrams of main systems are more likely to be reused while for auxiliary systems, since there are more different design solutions and possibilities, the reusability of the diagrams can be lower. Ideally every system and every different variant of the systems could eventually be implemented in the tool, in order to cover every design possible and by doing so, making the tool applicable to all the desired projects.

Quickness and ease of use

The tool surely has an intuitive structure and for this reason it is absolutely easy to apply. The quickness of use directly depends on the level of detail of the design which is analysed. In the case studies for example, the first application has been quick and effective while for the second case study, a more laborious procedure had to be performed. It is however essential to mention that the verification of the compliance of a such detailed design would have arguably required a much more extensive time without the tool. Furthermore, if the tool is applied since the very first stages of the design process as advised, every application will result quick and efficient, even in detailed design stages. In addition, some choices on the structure of the tool, e.g. the implementation of information about the relative position of the compartments only for the compartments for which is necessary for the assessment, has been evaluated as a smart solution to speed up the application of the tool also by the engineers at the Company. All in all the tool is considered easy to use, quick to apply the early stages and potentially even in the later stages if previous assessments have been performed.

13.3.2. Optional requirements

Even if defined "optional" during the literature review, great attention was given to these requirements during the development of the thesis project. In the following paragraphs is described how effectively the optional requirements have been satisfied.

Understanding of the possible criticalities in the design

If the notification of the not-achieved compliance was the ultimate goal of the thesis, necessary for the mitigation of the risks in the design, also great focus on the explanation of the type of issue was given during the coding of the tool. In this connection the tool is able to effectively report the type of issue in case of non compliant design. Indeed the tool's output includes the type of problem, the position of the issue as well as the components mispositioned in most cases. With this information the designer can easily understand the issue related with the compliance in the design, therefore the first optional requirement is considered fully satisfied.

Suggestion of solutions for design improvements

The code for the suggestion of the solutions in the software of the tool is as extensive as the code for the assessment of the compliance, proving the importance given to this requirement, even if optional. Indeed, multiple solutions have implemented in the tool, which can wisely advise the designer on how to overcome the issues with the compliance. The convenience of this additional feature has also been demonstrated in the first case study. During the case study emerged also the possibility of improving the accuracy in the provision of the solutions as well as the opportunity of widening the range of solutions. Nonetheless the tool is deemed to already provide viable and valuable solutions for the achievement of the compliance and therefore also this additional requirement is considered satisfied.

13.4. Conclusions

In conclusion, the tool developed is deemed to meet all the requirements set during the literature review, even the optional ones. Moreover, it was possible to demonstrate the efficacy of the project by applying the tool in two case studies. During the assessments, the tool performed as intended, mitigating the risks in the design of the Ro-pax ferry and confirming the compliance of the expedition cruise design. The tool is deemed applicable in the target stages of the process, and even capable to deal with the high detailed designs of the later stages. The assessment by means of the software resulted intuitive and efficient since the very first applications, also thanks to the effectiveness in reporting the potential criticalities in the projects. The additional functionalities implemented in the tool can suggest valuable design solutions, proved to be an useful support for the designers in case the compliance is not achieved in the first place. The overall usefulness of the tool has been immediately recognized by the engineers at DAMEN as well, which also see a great potential for further developments of the tool. Obviously, the software developed for the master thesis is to be considered part of a larger project, which should not be limited to duplicated systems, but should instead include all the types of systems and ideally even every possible variant of systems and auxiliary systems. Despite this, the tool developed for the graduation project is more than a "pilot model" and it already has, in facts, a practical utility as it was proven in the case studies. All in all, the results achieved are deemed more than satisfactory and for this reason the project is deemed worthy of being further developed.

13.5. Future work

During the development of the project and especially in the case studies and during the feedback sessions, many ideas to expand the model arose. These ideas are reported in this section, in order to describe all the possible next steps in the expansion of the project. First of all, clearly all the other systems and categories of systems have to be implemented in the tool. Even if this task has not great academic value since the feasibility of the project has already been proven, it will significantly increase the practical usefulness of the tool as daily support for the engineers at the Company. Another pragmatic improvement of the tool would certainly be the enlargement of the range of solutions and the enhancement of the accuracy in their suggestion, as was pointed out in the first case study. The tool could for example discard the unfeasible options for every situation, and even rank the feasible ones. Even if in Chapter 10 it is claimed that ranking the the diverse design solutions is very complex due to the the considerable amount of parameters influencing the "optimality" of the solutions, it is possible to select the criteria deemed the most important (e.g. costs) and rank the feasible solutions accordingly. Furthermore "optimality" criteria could also been implemented in the "move component" function. Indeed the tool could potentially suggest which among the compartments in which it is possible to move the misplaced components are a better design solution. Some criteria like proximity to compartments with components of the same subsystem type or closeness to dependant equipment in order to reduce the routing of the system are to be figured out.

Another potentially significant improvement in the expansion of the model could be matching the code of the tool with drawings of the ships on a CAD software. This would be particularly useful in the later stages the design, when information about the relative position of the compartments and even their characteristics could directly be drawn from the CAD model. Also, visual representation of the problem on the CAD would be possible, allowing an even better comprehension of the issue with the compliance. In this connection some engineers at DAMEN ENGINEERING HELSINKI are already working on Python scripts to run on top of Rhino software. The possibility of merging different programs in order to take advantage of useful features in the other models could significantly enhance the potentiality of the tool.

Many other ideas could be implemented in the tool to expand the functionalities next to the initial purpose of assessment tool for SRtP projects. For example, the diagrams of the systems could be coded with additional information such as the area required for each component with respective piping, cabling and auxiliary equipment in order to give indications about the volume of the compartments in which they are placed. This could be an extremely useful feature especially in the early stages for a preliminary sizing of the spaces.

To conclude, the possible ideas to be implemented to expand the tool are almost unlimited, bounded by the only fantasy of the developers. It is however suggested to perform the steps of its further development progressively. First, the model should be completed, then it can be improved, and finally it will be possible to expand it with the aid of creativity, without losing touch with pragmatism, and always ruled by scientific rigor.

13.6. Personal experience

While the graduation project approaches its conclusion, it is possible to draw some personal considerations on the overall experience. I must say that despite the large amount of work condensed in few months, I will certainly remember the master thesis period as a gratifying and pleasant time. Indeed next to the possibility to increase the knowledge in the subject of the degree, I had the opportunity to live precious personal experiences. First of all, the internship at DAMEN allowed me to experience the daily routine of the engineers at the Company and to witness some of the internal dynamics of a large industrial group. Sadly, the time at the company has been suddenly interrupted by the global pandemic for which 2020 will be remembered in the coming decades, but even this unfortunate event gave me the opportunity to learn something. During the "quarantine" period, home turned out to be a surprisingly productive place to work, contrary to what I always believed. Furthermore, during the graduation project I also certainly improved in time management. Indeed I was able to meet all the important deadlines in advance and even the strict personal deadlines that I used to set for every week of work. Since I managed to conclude the project on time, despite the large amount of work and the ambitious time-span, I can say the time management strategy applied was effective and I will likely re-use it for important projects in a future working career.

On an academic point of view, I significantly deepened my knowledge about regulations. I had the opportunity to thoroughly study an important framework such as SRtP regulations, which I consider a very important expertise given the large impact on the industry. In this connection, I also got to know how overbearing is the regulatory world and how much it affects the everyday work of the engineers. Next to the the regulations I also had the opportunity to analyse some of the most important systems installed in passenger ships and to learn their complexity and some of the challenges in their design. To conclude, if I look back to when the graduation project started, I can definitely say that my knowledge on the topic significantly increased but also that during this period I experienced a valuable personal growth.

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A

Validation tests

Description issue given in input	Input 1	Input 2	Output
Two components in the same MVZ	M1	M1	If MVZ 1 is lost, both subsystems are affected. There are 1 components of Subsystem A (['Component A']) and 1 components of Subsystem B (['Component B']) not protected. Some components must be moved
Two components in same MVZ, one protected	M1	M100R	System compliant
Two components in same MVZ, with detailed space definition	F133	W111	If MVZ 1 is lost, both subsystems are affected. There are 1 components of Subsystem A (['Component A']) and 1 components of Subsystem B (['Component B']) not protected. Some components must be moved
Two components in same watertight compartment	W411	W411	There are components of both subsystems in the same Watertight compartment W411 (['Component A'] of Subsystem A and ['Component B'] of Subsystem B). In case of flooding in this space both subsystems would be affected, some components must be moved.
Two components in same fire boundary (with FFF)	F343P	F343P	There are components of both subsystems in the same Fire boundary F343 (['Component A'] of Subsystem A and ['Component B'] of Subsystem B)). In case of fire in this space both subsystems would be affected.
Two components in same fire boundary (no FFF)	F343	F343	There are components of both subsystems in the same Fire boundary F343 (['Component A'] of Subsystem A and ['Component B'] of Subsystem B)). In case of fire in this space both subsystems would be affected.
Two fire boundaries on the same deck	F343	F342	Install fixed fire fighting system in F342, a fire casualty could spread into F343 where there are components of a different subsystem. Alternatively move critical components. The fire could also spread from F343 to F342 since they are adjacent. Install fixed fire fighting system in both compartments.
Two fire boundaries, one on the deck above	F343	F331	Install fixed fire fighting system in F331 or move components. It could spread into F343 and Component A would be lost
Fire boundary and watertight compartment, same deck	F113	W112	Install fixed fire fighting system in F113 or move components. It could spread into W112 and Component B would be lost
Fire boundary and watertight compartment on deck above	F113	W123	Install fixed fire fighting system in F113 or move components. It could spread into W123 and Component B would be lost
Fire boundary and trunk (with A60) on same deck	F113	T111P	System compliant
Fire boundary and trunk (no A60) on same deck	F113	T111	Install fixed fire fighting system in F113, install A60 protection in T111 or move components (Component A would be lost in case of fire). If T111 can be origin of a fire, the casualty could spread into F113

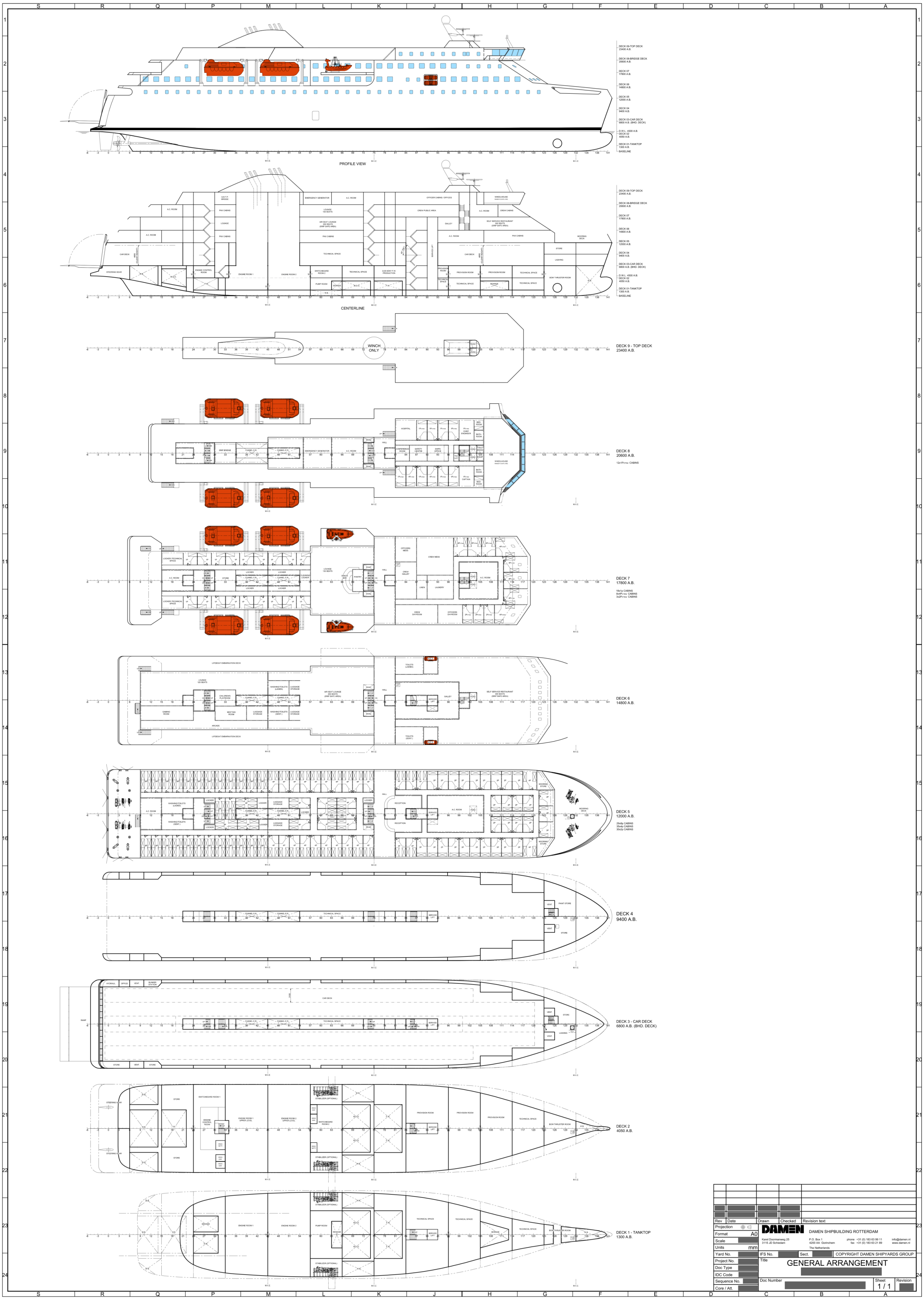
Table A.1: Validation tests - Compliance (Table 1)

Description issue given in input	Input 1	Input 2	Output
Fire boundary and trunk (no A60) on deck above	F113	T121	Install fixed fire fighting system in F113, install A60 protection in T121 or move components (Component A would be lost in case of fire).
Fire boundary and trunk (with A60) on deck above	F113	T121P	System compliant
Fire boundary and generic space on same deck	F113	G114	Install fixed fire fighting system in F113 or move components. It could spread into G114 and Component B would be lost
Fire boundary and generic space on deck above	F113	G122	Install fixed fire fighting system in F113 or move components. It could spread into G122 and Component B would be lost
Two components in same trunk (with A60)	T521P	T521P	In the same trunk with non-negligible fire risk (T521) there are components of both subsystems (['Component A'] of subsystem A and ['Component B'] of subsystem B). Since it can be origin of a fire, in case of casualty both subsystems would be affected.
Two components in same trunk (no A60)	T522	T522	In the same trunk with non-negligible fire risk (T522) there are components of both subsystems (['Component A'] of subsystem A and ['Component B'] of subsystem B). Since it can be origin of a fire, in case of casualty both subsystems would be affected.
Trunk and watertight compartment on same deck	T312	W311	Install fixed fire fighting system in F312 or move components. It could spread into W311 and Component B would be lost
Trunk and watertight compartment on deck above	T312	W322	Install fixed fire fighting system in T312 or move components. It could spread into W322 and Component B would be lost
Trunk and generic space on same deck	T312	G312	Install fixed fire fighting system in T312 or move components. It could spread into G322 and Component B would be lost
Trunk and generic space on deck above	T312	G322	Install fixed fire fighting system in T312 or move components. It could spread into G322 and Component B would be lost
Two trunks on same deck	T311	T312	Install A60 protection in T311 to avoid the spreading of the fire outside the space of origin or in T312 to protect the components inside. The fire could also spread from T312 to T311 since it can originate a fire and the two compartments are adjacent. Install A60 protection in both compartments.
Two trunks, one on deck above	T322	T312	Install A60 protection in T312 to avoid the spreading of the fire outside the space of origin or in T322 to protect the components inside (Component A would be lost in case of fire).

Table A.2: Validation tests - Compliance (Table 2)

B

General Arrangement plan case study 1


PROFILE VIEW
CENTERLINE
WINCH ONLY
DECK 9 - TOP DECK
23400 A.B.
DECK 8
20600 A.B.
DECK 7
17800 A.B.
DECK 6
14800 A.B.
DECK 5
12000 A.B.
DECK 4
9400 A.B.
DECK 3 - CAR DECK
6800 A.B. (BHD. DECK)
DECK 2
4050 A.B.
DECK 1 - TANKTOP
1300 A.B.
DAMEN
DAMEN SHIPBUILDING ROTTERDAM
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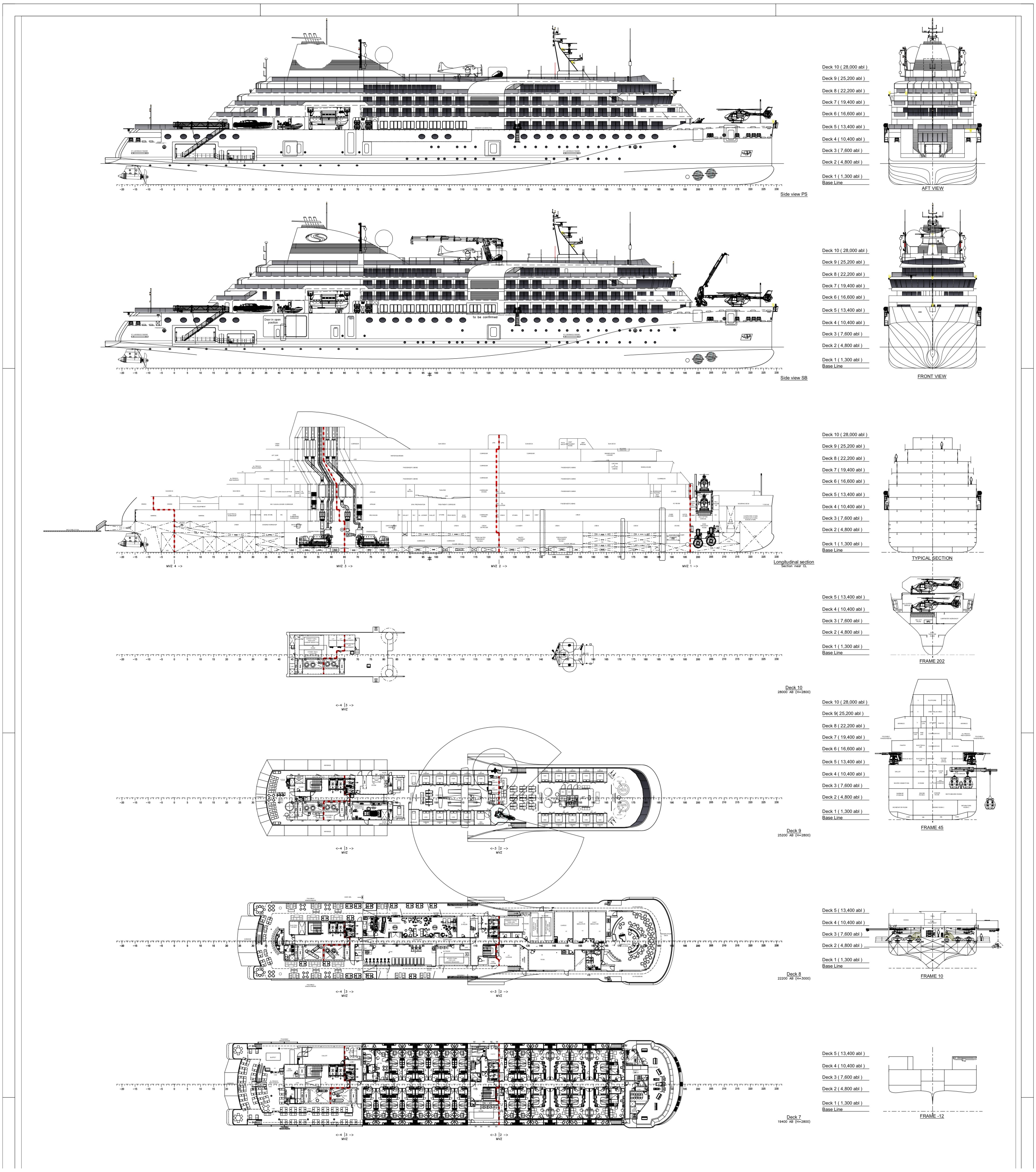
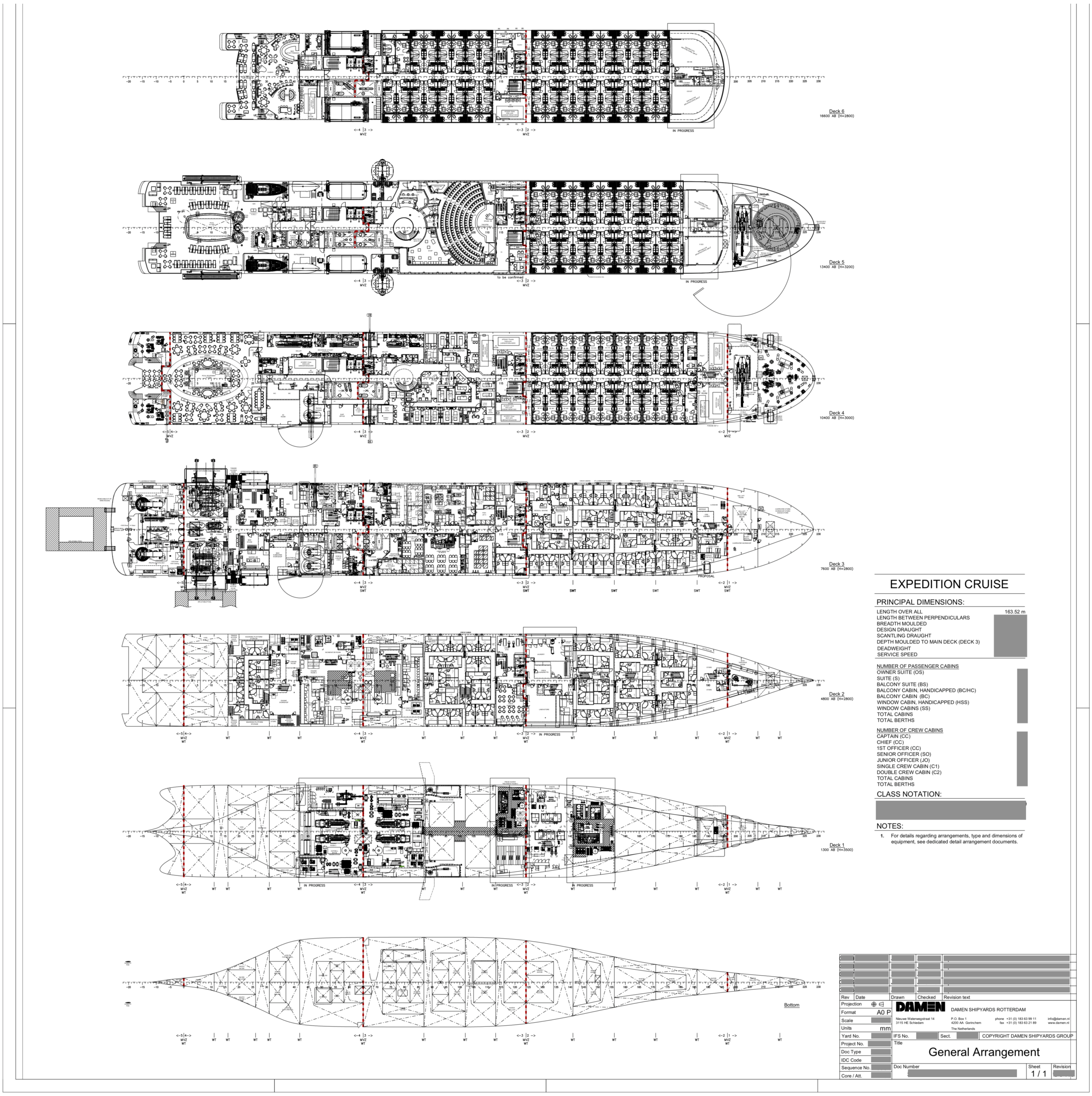
GENERAL ARRANGEMENT
Format A0
Sheet 1 / 1

C

General Arrangement plan case study 2


Deck 10 (28,000 abl)
Deck 9 (25,200 abl)
Deck 8 (22,200 abl)
Deck 7 (19,400 abl)
Deck 6 (16,600 abl)
Deck 5 (13,400 abl)
Deck 4 (10,400 abl)
Deck 3 (7,600 abl)
Deck 2 (4,800 abl)
Deck 1 (1,300 abl)
Base Line
Side view PS
AFT VIEW
Side view SB
FRONT VIEW
to be confirmed
Longitudinal section
TYPICAL SECTION
FRAME 202
Deck 10
FRAME 45
Deck 9
Deck 8
FRAME 10
Deck 7
FRAME -12


Deck 6
Deck 5
Deck 4
Deck 3
Deck 2
Deck 1
Bottom
IN PROGRESS
EXPEDITION CRUISE
PRINCIPAL DIMENSIONS:
LENGTH OVER ALL 163.52 m
LENGTH BETWEEN PERPENDICULARS
BREADTH MOULDED
DESIGN DRAUGHT
SCANTLING DRAUGHT
DEPTH MOULDED TO MAIN DECK (DECK 3)
DEADWEIGHT
SERVICE SPEED
[redacted]
NUMBER OF PASSENGER CABINS
OWNER SUITE (OS)
SUITE (S)
BALCONY SUITE (BS)
BALCONY CABIN, HANDICAPPED (BC/HC)
BALCONY CABIN (BC)
WINDOW CABIN, HANDICAPPED (HSS)
WINDOW CABINS (SS)
TOTAL CABINS
TOTAL BERTHS
[redacted]
NUMBER OF CREW CABINS
CAPTAIN (CC)
CHIEF (CC)
1ST OFFICER (CC)
SENIOR OFFICER (SO)
JUNIOR OFFICER (JO)
SINGLE CREW CABIN (C1)
DOUBLE CREW CABIN (C2)
TOTAL CABINS
TOTAL BERTHS
[redacted]
CLASS NOTATION:
[redacted]
NOTES:
1. For details regarding arrangements, type and dimensions of equipment, see dedicated detail arrangement documents.
[redacted]
Rev Date Drawn Checked Revision text
Projection
Format A0 P
Scale [redacted]
Units mm
DAMEN SHIPYARDS ROTTERDAM
Nieuwe Waterwegstraat 14
3115 HE Schiedam
P.O. Box 1
4200 AA Gorinchem
The Netherlands
phone +31 (0) 183 63 99 11
fax +31 (0) 183 63 21 89
info@damen.nl
www.damen.nl
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Sequence No. [redacted]
Core / Att. [redacted]
Title
General Arrangement
Doc Number [redacted]
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Revision [redacted]