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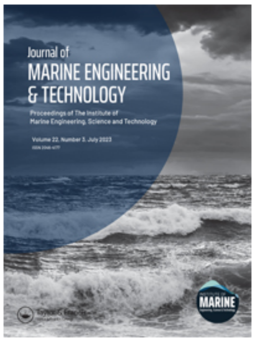

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A method to assess the impact of safe return to port regulatory framework on passenger ships concept design

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ABSTRACT

The introduction of the 'Safe Return to Port' (SRtP) regulations strongly impacted the design of passenger ships. To meet the functional requirements of these regulations, the systems on board reached an extreme level of complexity in terms of redundancy and segregation, considerably increasing the difficulties to assess the compliance of the designs. However, non-compliant designs are a major risk for every design company which must prevent at all costs the possibility of expensive re-designs in later stages of the process. The aim of this research is to address the gap in the literature and in the market of design support tools, presenting a method to effectively mitigate the risks of non-compliant solutions with SRtP. The method comprises a thorough analysis of the spaces on board and a software tool for the assessment of the correct placement of the systems components. The value of the solution proposed was assessed in two case studies in which the method has been proven capable of effectively identifying the non-compliant solutions in a convenient and time-saving manner. Additional features for the suggestion of solutions to achieve the compliance have been implemented in the tool to further support designers during the complex design process of SRtP projects.

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1. Introduction

The expansion of the cruise tourism over the past decades has led to a rapid surge, not only in vessel number but also in vessel capacity. With the growth of the number of passengers on a single vessel, also the risk associated to this branch of the shipping industry increased. 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 2000s the International Maritime Organization (IMO), during its 82nd session in 2006, approved a package of amendments to regulations dedicated to large passenger ships (IMO 2006a). These regulations are commonly known as 'Safe Return to Port' (SRtP) requirements. 'Safe Return to Port' caused a dramatic revolution in every aspect of the life of passenger ships, and especially in the shipbuilding industry where the changes in the ships architecture led to the need to rethink the conventional design procedures (Vicenzutti et al. 2016). Indeed the introduction of the SRtP framework significantly affected the business of ship-owning companies, shipyards and also design companies which face with the risks entailed by these regulations on a daily basis. The complexity required to the designs, and more specifically to the systems, to meet the performance standards set by SRtP, in fact significantly increases the risks in the design process due to the difficulties in assessing the compliance with the regulations. Clearly reducing the possibility of expensive re-designs in later stages of the process is mandatory to improve the performance of the companies. This research intends to address the difficulties and the hazards associated to the adoption of SRtP standards and it has the aim of mitigating the risks entailed by SRtP regulations. The goal of the study has been achieved through the synthesis of a new method for the effective mitigation of the risks of non-compliant solutions with 'Safe Return to Port' (SRtP) during the design process. The proposed method comprises two parts. First, an accurate analysis of the spaces on board, necessary to identify the characteristics and the attributes of the different spaces. Each space is labelled with an unique code (explained in detail in Section 4.2) which is used to input the position of different systems components in the software tool. The computer application is the second part of the presented method, and it is meant to assess the correct placement of the components of systems and sub-systems to ensure the required level of capability after a casualty which might damage one or more areas on board. The software, programmed in *Python*®, includes an user-friendly interface developed with *QT-Designer*® which conveniently shows the diagrams of the systems for the input and output of the software, facilitating the assessment process. Additional features such as the suggestion of different solutions in case of non-compliant designs were included in the software, making it a full-fledged design tool and therefore increasing the scientific and commercial value of the research. In the following paragraphs, the main concepts and impacts of SRtP regulatory framework will be explained, then the research gap will be described and the requirements for the method introduced. Finally, in the last sections, the results of the research will be presented. The solution proposed meets the ultimate goal of mitigating design risks in the early stages of SRtP projects, although it is deemed capable to support designers even in more advanced design phases. The method satisfies the requirements determined based on the needs of the shipbuilding industry and it has, in facts, a noticeable commercial value in addition to the academic interest. The commercial relevance, together with the effectiveness of the method in achieving the objective and requirements of the research, was assessed through two case studies, reported in the last section of the manuscript before Conclusion, where some final considerations are drawn.

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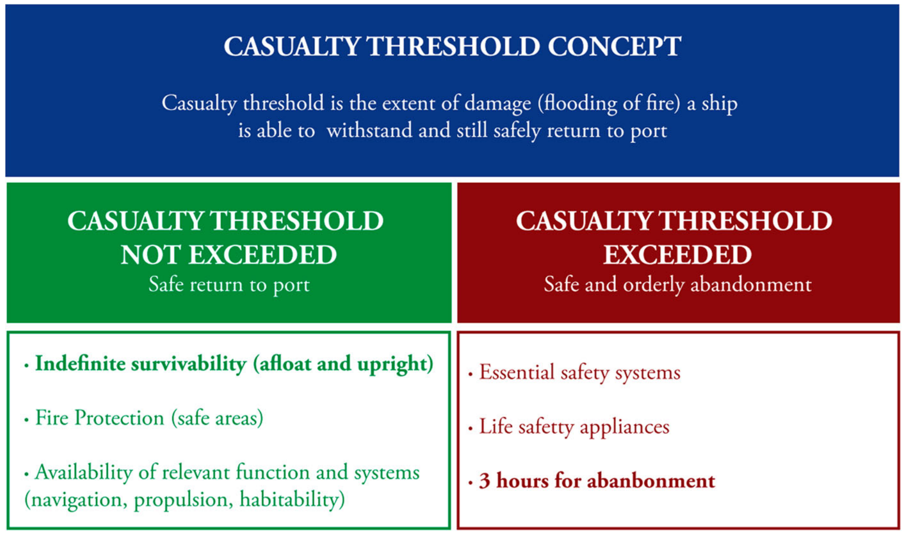

Figure 1. The IMO framework – passenger ship safety (Vassalos 2009).

2. Safe return to port regulatory framework

A complete understanding of the challenges set by these regulations and the impact and consequences of their implementation is fundamental for the proper development of the desired support method.

2.1. Intention, goals and concept of SRtP regulations

Safe Return to Port are goal based regulations introduced 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 its own best lifeboat. The Safe Return to Port regulations apply to all passenger ships with a length of 120 m or more, or with at least three Main Vertical Zones (MVZ), having their keel laid after July 2010 (IMO 2006a). The rules outline two scenarios, with different requirements for different extent of casualties (Figure 1):

- *Safe Return to Port* (SRtP) (IMO 2006b, 2006c), 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. For this scenario, the regulations identify 13 essential systems that must remain operational to grant the required performance of the ship as well as a defined level of habitability for the passengers accommodated in 'Safe Areas' on board.
- *Orderly Evacuation and Abandonment of the ship* (OEA) (IMO 2006d), if the casualty exceeds the defined threshold the ship should maintain the capability to allow the passengers to evacuate and abandon the ship. In this scenario, SOLAS II-2 Reg. 22 identifies 6 systems that must remain operational for at least 3 h in all Main Vertical Zones not affected by the casualty.

2.2. Impact of SRtP

Repercussion of these regulations can be found in every aspect of the industry, from commission to operations and obviously in the design of passenger ships. Indeed the implementation of these regulations caused a dramatic revolution of the design procedures (Cangelosi et al. 2018), and design companies have been greatly affected. Vicenzutti et al. (2016) distinguish two levels of impact on ship design: direct impact and indirect impact.

2.2.1. Direct impact

The direct impact can be summarised as the need to redesign certain systems 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. 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 system elements, cables and piping included, which was not a priority before SRtP.

2.2.2. 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. Proving the compliance is necessary to avoid the possibility that the design will be eventually rejected, which clearly is another source of risks during the design phase.

Thus the high complexity required in the design of the systems and the need of demonstrating the compliance are both a significant source of risks for design companies. In this context, a thorough mitigation of the risks entailed by SRtP regulations coincides with a careful analysis of the compliance of the designs. Indeed, if the compliance is assessed at every stage of the process, the risk of redesign due to the non achievement of the performance standards required for the systems and also the possibility of being rejected by the Classification Societies is fairly reduced.

3. Assessment of the design

It is understood that a correct assessment of the design throughout the design process can effectively mitigate most of the risks entailed by SRtP regulations. However, the assessment of the compliance of the design and, more specifically, of the systems, is not as simple as it may seem. 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. 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. The design process is often characterised by a tight schedule and also the time pressure can be a potential source of risks. In this connection, a tool could speed up the evaluation process and reduce the possibility of mistakes in the assessment made by the designers. 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.

3.1. Requirements of the method

Thanks to the opportunity to closely see the work process for passenger ships at the Design office at DAMEN, it has been possible to better understand the challenges and the risks entailed by SRtP, and to formulate the requirements of a tool to support designers in the difficult task of the evaluation of the compliance with the regulations. 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. Indeed 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 has a low level of detail, and the tool should not require more information than the one available to be applied.

An additional requirement is the 'convenience' of the tool in terms of quickness and ease of use. In fact, a tool 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 noncompliant design. In other words, it should not work as a 'black box' in which the designers input some information regarding the design 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 defects 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 to make the design compliant.

3.2. Research gap

Even if support tools are deemed necessary to help designers throughout the whole complex design process of ships compliant with Safe Return to Port, there are few software products or models available in the market or in the 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 passenger vessels market 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 (Cangelosi et al. 2018). 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 environments 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 (Ruth and Rognebakke 2019), FREDYN (Walree 2010), NAPA (NAPA 2020), PIAS (SARC 2020), simulate flooding in the ship and they can therefore be applied to SRtP scenarios. In addition to the software available in the market, regarding the stability of the vessel, many models have been developed by researchers to study the behaviour of a damaged ship in SRtP scenarios. Spanos and Papanikolaou (2011) for example analysed the survivability of damaged ROPAX vessels. Espinoza Haro et al. (2017) investigated the motion responses and flooding behaviour of a damaged passenger ship advancing in waves. Other research projects focus on the availability of systems in damage scenarios, although not in an SRtP context. Some of the models developed for naval defence industry available in the literature for example can be used to assess the vulnerability of distributed systems even in the early stages of the design process (van Diessen et al. 2021).

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 (2020), Global Maritime (2020) and Deltamarin (2020). However, these software products require a good level of detail of the design to work, and they cannot be used for an effective mitigation of the risks in the early stages of the design process. Moreover, the amount of time needed to model the design in these tools is considerable (up to 0.5 manyear). Also for this reason it is deemed illogical applying these software products in the early stages of the design process when even the requirements of the vessel are uncertain.

In the paragraphs above, 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. Furthermore, the support tools available in the market and in the literature have been discussed, and a gap in the research has been found. Thus the result of this analysis 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 risks, this evaluation has to be performed since the very beginning of the design process 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 research project is filling this gap.

4. Goal method for the mitigation of the risks

The proposed method is intended to mitigate risks in the design process of SRtP projects. It is important to recall that a design risk, with regard to this research, consists in the possibility to implement non-compliant design solutions which must be corrected in later stages of the process causing the company to incur in time losses and high costs. Since Safe Return to Port regulations 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 since the early stages of the process by verifying the correct placement of the components of the essential systems. 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.

4.1. Space definition

The definition of the spaces on board is considered the basis of the design of Safe Return to Port projects because it is indispensable for the correct arrangement of all the systems (components, piping and cabling). The space definition in SRtP projects is often referred as 'Casualty Threshold plan' (Hovden 2017), 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. 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. 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 can vary with the level of detail in the design, 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 Main Vertical Zones (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. 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 the following section.
- *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 fixed fire fighting system in the compartments is therefore essential to assess the extent of the fire. Similarly to watertight compartments, this type of spaces has as attribute the Main Vertical Zone and the deck. Moreover, the presence of a fixed fire-fighting system in the space is required as attribute, to properly assess the spreading of the casualty.
- *Trunks*. Trunks are spaces with their own assessment rules and they must therefore be analysed 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.

4.2. 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 analysed. For this purpose, a naming convention for the spaces on board has been created, in

Figure 2. Structure of the input for spaces.

order to label all the compartments defined on board with an identification string which will also be used to input the position of the systems components to be assessed in the software. The identification string, which contains information about the position of the spaces on board and their characteristics, is structured as depicted in Figure 2.The first entry represents the type of space. The different options, according to the space definition reported in Section 4.1, 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 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'. Clearly all the spaces attributes input in the software by means of the identification strings are essential information to be evaluated during the assessment of the compliance.

4.3. Assessment tool

The assessment tool is meant to evaluate the correct placement of the components of the essential systems. It basically consists in a software provided with an interface illustrating the diagrams of the systems, in which the user will input the string code of the compartment in which the components are located. The tool will then apply an 'assessment logic' derived from the regulations and coded in the software, to assess the compliance of the system. To identify the assessment logic, an analysis on the systems required by the regulations has firstly been performed. This analysis was necessary to evaluate the possibility of a common assessment logic for all the systems on board. Clearly, due to the deep structural differences of the systems, a common assessment logic for all the systems soon appeared to be impossible. It was possible, however, to group the systems into families of systems sharing a similar assessment rationale. The categories 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 sub-systems, 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.

As a 'pilot model', a software for the first family of system was developed.

5. Assessment tool for duplicated systems

As mentioned above, the assessment logic for duplicated systems consists in verifying that, for all the casualties possible, at least one of the subsystems remains fully operational. Clearly, explaining the exact logic applied by the software to perform the assessment would be impossible, as the steps performed by the software are coded in scripts of several hundreds of lines. At high level, the main logic programmed in the model consists in simulating a casualty originated in each space defined on board (taking into account the different characteristics of the compartments as further explained in the following paragraphs), and in evaluating the consequences of that casualty considering the level of capability required by SRtP regulations. Since the regulations outline two scenarios, and that different systems have to comply with different scenarios, the extent of the casualty for which the system is tested must be selected by the user for each assessment. In other words, once the user will complete the input process, he will have to choose the testing scenario: SRtP for casualties within the threshold or OEA for casualty exceeding the threshold.

5.1. OEA scenario

The assessment for OEA scenario consists in considering one at the time all the MVZs lost and verifying that not both subsystems are affected. 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, and it will not be considered 'critical', even if mislocated.

5.2. SRtP scenario

For this scenario, the system will be tested for casualties within the casualty threshold. The assessment process will assess if at least one subsystem remains fully operational if all the spaces defined in input are origin of a casualty. The assessment in SRtP scenario is based on the space definition and it is performed differently for each space type.

5.2.1. Watertight compartments

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.

5.2.2. Fire boundaries

As for 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 in fact, the casualty cannot spread out to the space of origin, and the assessment is limited to the evaluation of the type of subsystems of the components installed inside. For fire boundaries without FFF, the assessment is more complicated. According to the regulations, 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). It is important to mention that some additional information is necessary for the correct assessment of the spreading of the fire. More specifically, when possible criticalities are found, the user will be asked to input information about the relative position of some compartments, to allow the software to evaluate if the fire can spread form one space to another.

5.2.3. Trunks

The assessment for trunks is for many aspects similar to the assessment for fire boundaries. 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. 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. According to the regulations in fact, if a trunk provided with A60 can be origin of a fire, the casualty is not consider to spread out to the space of origin (and into, if originated in a different compartment). The assessment in this case will be limited to the evaluation of the subsystem types of the components installed in the trunk. Conversely, if the trunk it is not provided with A60 fire protection and it can be origin of fire, 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. In this case, the assessment is performed in the same way as for fire boundaries and the user will be asked to fill in the information necessary for the complete assessment, that has not been input yet.

6. Solutions

Other than supporting the designers with the mitigation of the risks entailed by the regulations by assessing the compliance of the systems, the tool can further support the design process by suggesting some solutions to achieve the compliance, if 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. The tool in fact would not be able to assess which is the optimal design solution to undertake. 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.

6.1. Protection of the 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 output 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)'

The protection of spaces by means of FFF system and A60 class insulation is an effective strategy to solve many of the criticalities with the compliance, and should always be considered if applicable.

6.2. Installation of casualty resistant material

As it has already been mentioned, 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 it 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 resistan" 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 (DNV GL 2019). It is proposed anyways as it is still a feasible option to achieve the compliance.

6.3. Move component

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.

There are different functionalities for OEA scenario and for SRtP scenario. In the assessment of new possible locations for the mislocated components in OEA scenario, the user will select a subsystem type among the components that caused the issue with the compliance, and the tool will suggest in which MVZ is and is not possible to move the components of the selected subsystem. For the 'move component' functionality in SRtP scenario, the user will be guided in the choice of new compartments for the critical components. For this function, a dedicated interface has been developed (Figure 3). In the interface, it is possible to visualise 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. 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 from the ones originally defined in input.

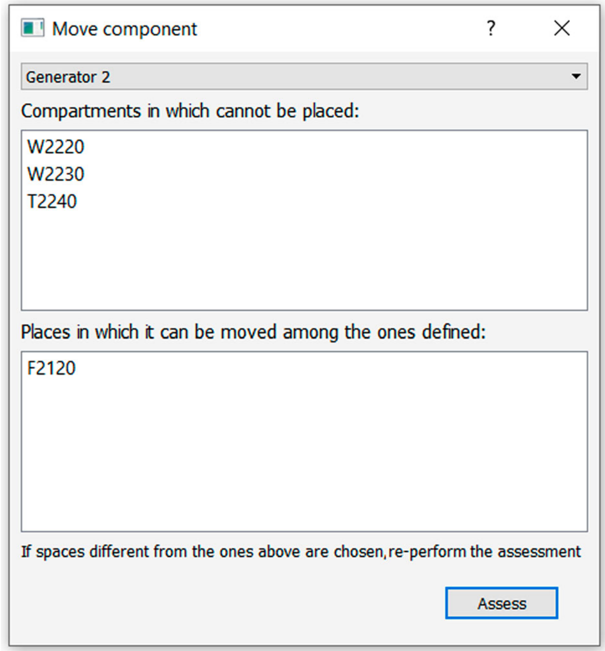

Figure 3. Interface 'Move component' functionality for casualties within the threshold. In the figure are reported the label strings (see Section 4.2) identifying the spaces on board in which the component 'Generator 2' can and cannot be moved as an example of the output of the functionality.

7. Application of assessment method

The application process of the method proposed 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 4, a flowchart illustrating the assessment process by means of the proposed method is provided.

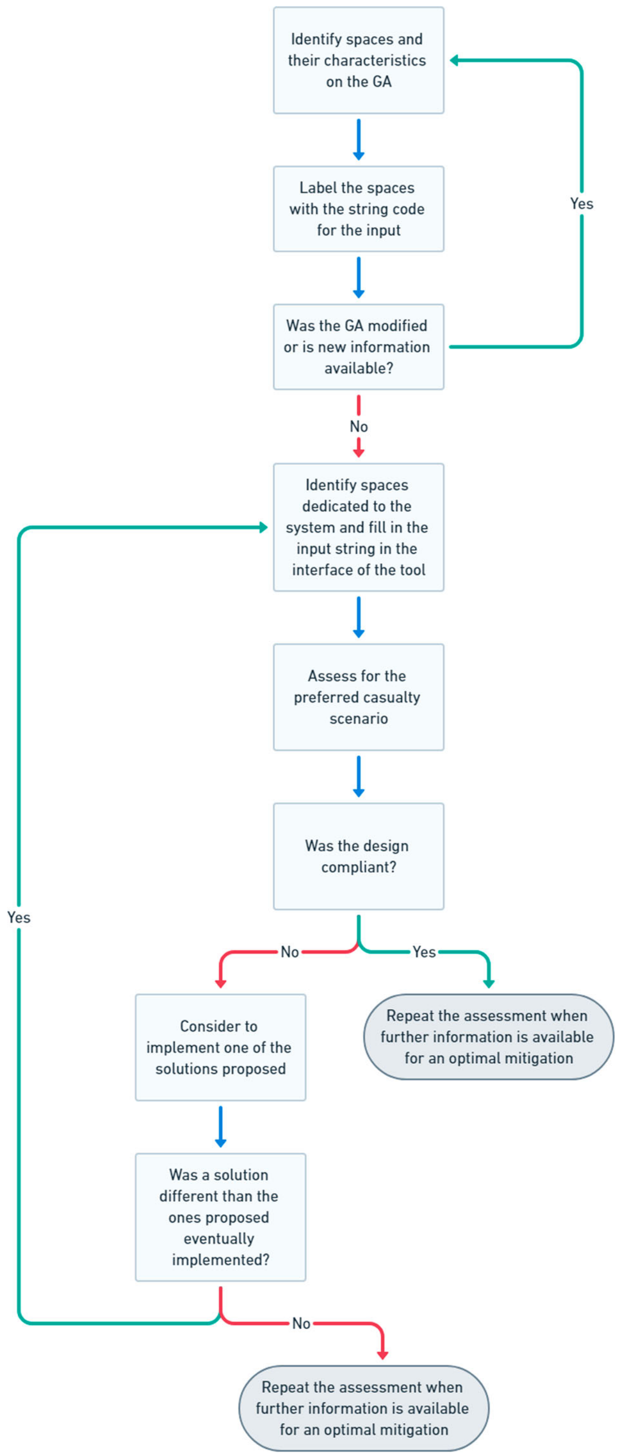

Figure 4. Application of the proposed method – workflow.

8. Case studies

After the tool has been verified and validated, it has been applied to two case studies to complete the testing strategy. For the case studies, the tool has been challenged with the design of two real projects: a ro-pax ferry and an expedition cruise. Other than a different type of vessel the two projects differentiate also for the level of detail. While the ro-pax ferry has been tested in the very first stages of design, the design of the cruise ship was carried on till advanced design phases and it was therefore much more detailed. This choice was purposely performed to identify the range of applicability of the tool within the design process. Furthermore, the design of the ferry was selected as it has been possible to recreate an actual issue with the compliance with SRtP occurred during the early design phases. In the second case study instead, the tool has been challenged in verifying the compliance of the detailed design of the cruise ship.

8.1. *Case study 1: Ro-pax vessel*

In the first case study, the method was applied to a very low detailed design of a Ro-pax ferry. Due to confidentiality of the projects, no details about the vessels will be disclosed. The goal of this case study was to find the noncompliant solutions implemented in the design and to test the effectiveness of the tool in the very first stages of the design process. In Figure 5, the first two decks of the vessel in question are reported.

Since the design consists of the preliminary drawings of the arrangement of the main spaces, no information about the components of the systems was available at this stage. The evaluation of the compliance with SRtP was then limited to the assessment of the arrangement of the main technical spaces and also of the fuel oil tanks. For this purpose, a diagram of the Fuel Oil system was implemented in the tool (Figure 6). 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 a result of the assessment an issue with the compliance of the systems was reported. It resulted in fact that the storage tanks were positioned in two adjacent fire boundaries in the same MVZ. Indeed if that MVZ was lost in a fire casualty, as the OEA scenario prescribes, both subsystems would be affected and the power generation would fail too. The solution proposed by the tool in this situation, and the only one possible, was to move one of the storage tanks in different MVZ, also providing the feasible options.

Other than the assessment of the tank arrangement, also the spaces dedicated to the Propulsion systems were tested, this time for casualties within the threshold (SRtP scenario). After the assessment, the two compartments dedicated to the azimuth thrusters and their auxiliary equipment resulted to be non-compliant with the regulations. Indeed, being two adjacent fire boundaries not provided with FFF system, whatever casualty originated in one of the two compartments would affect both propulsion systems. The solution proposed by the tool was the installation of an active fire extinguishing system in both compartments. The tool also suggested moving the components as possible option to achieve the compliance. However, the azimuth thrusters are strictly dependent on their position on board, and they cannot be moved elsewhere. This situation showed that the accuracy in the suggestion of the solutions can be improved, for example by implementing position constraints for some components directly depending on their position.

8.2. *Case study 2: expedition cruise*

For the second case study, the tool was applied to a very detailed design of an expedition cruise. The goal of this case study was to test the applicability of the method in the advanced stages of the design process, when most of the details about spaces and systems are available. In Figure 7, the first two decks in the GA of the cruise ship are reported. The tool was challenged in verifying the compliance of the Propulsion and Power Generation (PG) systems. Clearly also all the auxiliary systems, on which the PG system is dependant, had to be tested at the same time to evaluate the availability of power in every casualty scenario. The auxiliary systems considered in this assessment were:

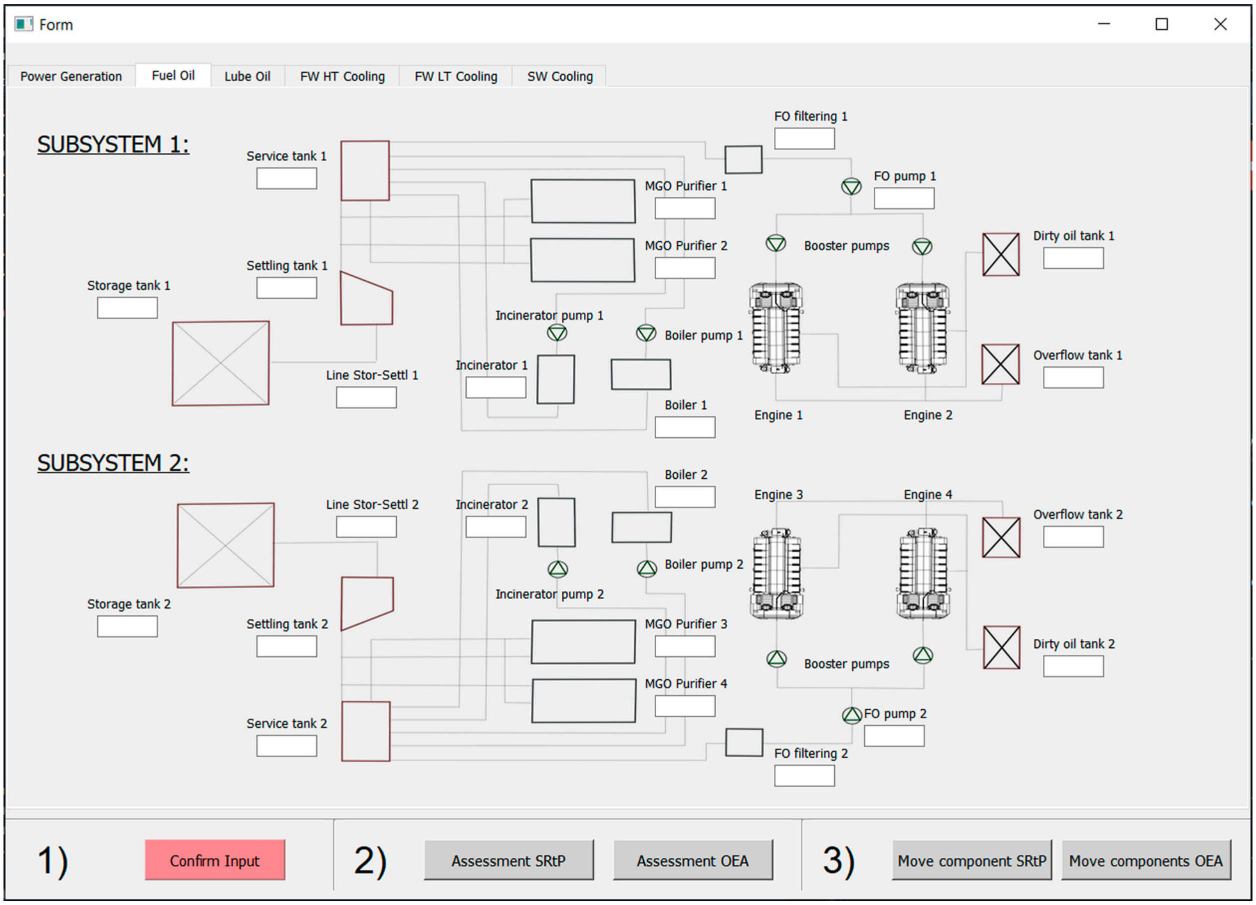

Figure 5. First two decks of the Ro-pax vessel.

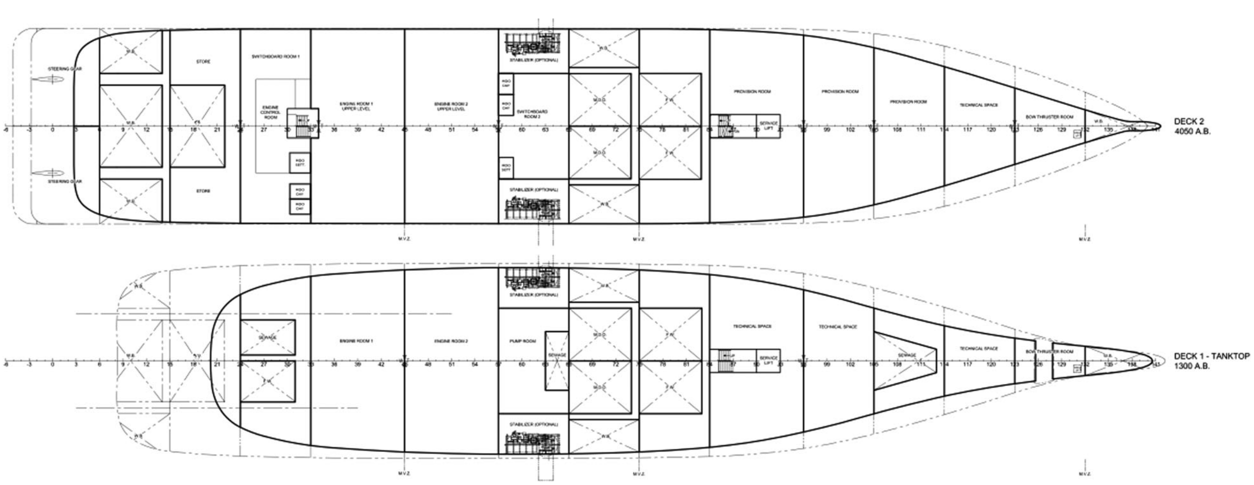

Figure 6. Interface for the assessment of Fuel Oil system.

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

Since only the software for duplicated systems was implemented in the tool, the assessment was limited to the systems of the first family (see Section 4.3). However, all the auxiliary systems considered in the second case study were designed with the same redundancy level as the Power Generation system and they were, in fact, duplicated. When the whole system was not duplicated, as in the case of the Power Distribution system, only the duplicated parts have been included in the assessment. It is also important to mention that the

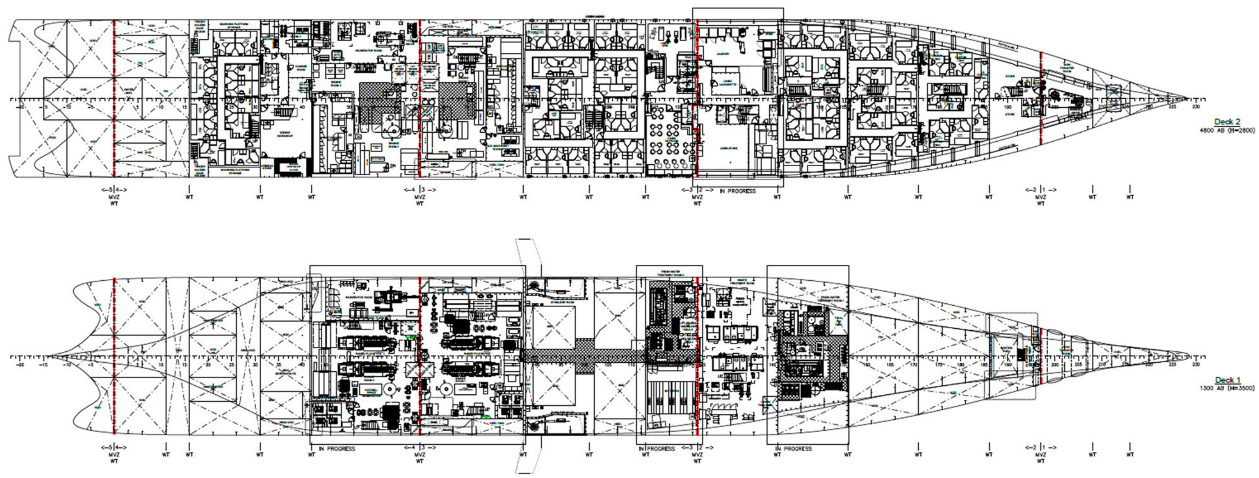

Figure 7. First two decks of the expedition cruise.

Power Generation and the Propulsion systems have been tested for different casualty scenarios. Indeed, while the propulsion systems are not required to remain operational for casualties exceeding the threshold, the Power Generation system has to function even in OEA scenario.

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 was concluded to remain available even for casualties exceeding the threshold. Even if it 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. For example, the space definition procedure was challenged with a design with great compartmentation and high level of detail. Despite the laborious work, the categorisation of the space was deemed suitable for the assessment of a detailed GA without further rules or assumptions.

8.2.1. Final considerations on the case studies

After the application of the tool in both case studies, the tool was 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 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. 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.

9. Conclusion

The main achievement of this project has been filling the gap in the research by successfully developing a method to mitigate the risks entailed by Safe Return to Port regulations, able to prevent expensive re-designs of the vessel during the design process. However, another remarkably important achievement was the development of a tool which has, in facts, a commercial interest besides its scientific value. Indeed this accomplishment has been possible thanks to an accurate determination of the requirements for the tool, clearly determined with the aim of filling the gap in the literature but also wisely selected based on the needs of the industry. It is therefore evident that, to draw conclusions on the value of this research, it is necessary to evaluate how effectively the presented solution satisfies the requirements set for the method. In this last section, great attention will be dedicated to this assessment, which combines the insights gained in the case studies and the knowledge of skillful designers, carried out through a long and thorough test phase.

The first requirement was obviously the ability of the tool to assess the design, which has been tested during the case studies. Indeed the method 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), always succeeding in the assessment. Also the opinion of the engineers was asked in this regard and once again the tool was deemed an useful support in the design process. Concerning the computational power, the second requirement, 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). As third requirement, the tool was asked to be applicable to low detailed designs, in order to mitigate the risks of non-compliant solution since the beginning of the process. In this regard, in the first case study, the tool has been tested on the design with the lowest level of detail among the General Arrangement plans provided by DAMEN, proving to meet the requirement. In addition, with the second case study, it has been demonstrated that the method is capable to deal also with very detailed designs, being limited only 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 reusability of the tool, the fourth requirement, directly depends on the reusability of the systems diagrams implemented in the software. Even if the same diagrams (Fuel Oil system and partially Propulsion system) have been used for both case studies, to have a full comprehension of the tool's reusability it has been necessary to resort to the opinion of the system engineers at DAMEN. It was evident that the more detail is implemented in the diagrams of the systems, the less generic they become and therefore, less reusable. Regarding the last 'essential' requirement, namely the quickness and ease of use of the tool, not many considerations have to be drawn in this regard, as the tool immediately appeared to be a practical and intuitive support with great time-saving potential.

During the development of the project great attention was also given to the 'optional' requirements. The first one was the possibility of explaining of the criticalities in the design. In this connection the tool is designed to effectively report the type of issue and where it occurs in case of non-compliant design. Finally, the last requirement was the possibility to suggest design solutions to improve the design. 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. Indeed, multiple solutions have implemented in the tool, which can wisely advise the designer on how to overcome the issues with the compliance, a considerable achievement for the project. The convenience of this additional feature has been demonstrated in the first case study, where the tool provided viable and valuable solutions for the achievement of the compliance, therefore also this additional requirement is considered satisfied.

In conclusion, the method developed is deemed to meet all the requirements for an effective mitigation, filling the gap in the research. The overall usefulness of the method has been immediately recognised 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 initial research project 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 this research is more than a 'pilot model' and it already has, in fact, a practical utility as it was proven in the case studies.

Among the next possible steps for the projects, besides the enlargement of the range of solutions and the enhancement of the accuracy in their suggestion (as pointed out in the first case study), the tool could for example discard the unfeasible suggested options for every situation. These improvements are the moderately difficult to implement and could be addressed in a few months of work. Scaling up with the complexity of potential developments for the tool, 'optimality' criteria could be implemented to rank the suggested solution, so to advise on which, among the proposed solutions, would result in a better design. Some criteria like proximity to compartments with components of the same subsystem type or closeness to dependent equipment in order to reduce the routing of the system are to be figured out. Additional criteria could take into account the operational costs of the systems other than the installation costs, for example, many studies have investigated the possibility to optimise the design of power systems to improve the energy efficiency (Jaurola et al. 2019). Despite the large research in this direction, optimise design solutions is a complex task which would require a large effort for both the engineering work, to design the 'optimality' rationale, as well as for the programming labor, to implement it in the software. 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. Although very complex and onerous to implement, this improvement would make possible to automatically collect information about the spaces from the CAD model, speeding up the assessment process, other than allow the visualisation of the non-compliant solutions directly on the drawings for an even better comprehension of the issues.

Clearly, many ideas of further developments of the tool arose during the execution of the project, 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 the needs of the industry. Even though some of the suggested further developments of the tool exceed the research goal of mitigating design risks entailed by the SRtP regulatory framework, it is important to reiterate the difficulties of design companies in meeting the demanding requirements of SRtP regulations and the importance of a support tool for the mitigation of the risks associated. Furthermore, despite the dramatic hit the cruise industry suffered after the global pandemic of 2020, the industry will certainly recover, the safety of passenger will still be the top priority of regulatory institutions which might even opt for stricter rules in the future. For this reason, it would be important for design companies in the sector to invest in design support tools, to be competitive today and to prepare for tomorrow.

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No potential conflict of interest was reported by the authors.

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