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Bulkheads' Position Optimisation in the Concept Design of Ships under Deterministic Rules

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Abstract: The position of the transverse bulkheads is the most important aspect in determining the internal subdivision of the ship and has a strong impact on the general arrangement, weight distribution and capacity of the ship. Nowadays, deterministic rules still apply to various types of ships such as gas carriers, naval ships, icebreakers, etc. For these vessels a new floodable length can be defined as the extent of the ship that can be flooded, still assuring compliance with the damage stability criteria. The main objective of this paper is using the floodable lengths to optimize the position of bulkheads. The proposed methodology maximises the margin between the floodable length and the actual flooded length, which consists of two lost contiguous compartments. This method, applicable in the framework of multi-attribute decision-making techniques for ship concept design, allows identification of the minimum number of bulkheads a ship requires, quantification, and maximisation of the safety margin for compliance with deterministic damage stability criteria. This margin ensures maximum flexibility for changes that may be required in the next design phases. The proposed method, based on a multi-stage optimization, is tested on a compressed natural gas carrier to define the minimum number and position of the transverse bulkheads dividing the cargo holds.

Keywords: ship concept design; deterministic rules; CNG ship; bulkheads positioning; optimisation; naval architecture; ship structures

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1. Introduction

The effectiveness of the ship's internal subdivision is mainly assured by transverse bulkheads that, after damage, limit floodwater spreading along the ship. Hence, the proper positioning of the bulkheads is a primary concern in ship design, not only from a safety perspective but also for the strong impact on the ship's internal layot [1]. Currently, most of the vessels shall comply with SOLAS probabilistic damage stability rules [2]. However, there are still several types of ships for which deterministic regulations apply. For instance, gas carriers shall comply with requirements coming from International Gas Code (IGC) [3], ships navigating in polar regions with requirements from Polar code [4] and all naval vessels are also subject to deterministic damage stability requirements, e.g., [5–7]. Therefore, a methodology to define the optimal subdivision for ships under deterministic rules might be helpful for the design of these special ships, implying complex design procedures and high economic value.

In the recent past, several studies addressed the topic of subdivision optimisation, mainly focusing on ships under SOLAS probabilistic requirements. In [8], multiobjective optimisation is employed in the early stage design of an Aframax tanker, where transverse bulkheads position is adjusted by allowing one web frame spacing shift fore or aft the original position. In [9], the optimisation of the subdivision of a passenger ship under SOLAS probabilistic rules is investigated, focusing on the challenges in optimisation problem definition and algorithm selection. Ref. [10] focused on the optimisation of the inner shell of a product oil tanker, using an improved particle swarm optimization algorithm. In [11], focus has been made on a shuttle tanker, applying a multi-objective optimisation to approach the Pareto frontier, considering prevention of pollution, economic benefit and safety. Only one study explored the optimisation of subdivision of a naval ship under deterministic requirements, but the method is not devoted to checking rule compliance, since it takes into account the probability of missile damage to maximise the average anti-wind capacity after damage [12]. Besides, multiple studies are focused on ship structures optimisation (e.g., [13–15]. However, these studies usually discard the issues related to damage stability.

When dealing with complex ships, the subdivision has a primary effect on the internal layout and is subject to several constraints due to main machinery size and weight, cargo capacity, harmonization with other structures, etc. It is a matter of fact that these aspects shall be considered since the initial stages of ship design [16], where most of the ship's performances (both technical and economic) are determined. However, the effectiveness of Multi-Objective Decision Making (MODM) techniques in concept design have been questioned for two decades [17]. Multi-Attribute Decision Making (MADM) methodologies based on statistics have been claimed to be more suitable for the selection of the main particular of a ship in the concept design [18]. Nevertheless, MADM outcomes can notably benefit from a better definition of ship geometry [19], usually limited to the main dimensions and hull coefficients. In particular, the definition of optimal bulkhead position in the concept design can ease the definition of the ship's weight breakdown. Besides, addressing the damage stability at this stage can avoid costly rework in the subsequent design phases due to gross mistakes made in concept one implying major changes in the bulkheads' number and position.

The objective of the present work is the definition of a novel technique to address bulkheads' position optimisation in the concept design of ships under deterministic damage stability rules. The method is supposed to be applied in the framework of MADM techniques [20,21], hence, it shall be kept as simple as possible to be run for hundreds of feasible design alternatives generated by Monte-Carlo sampling. The method is based on the definition of a new type of floodable length, first introduced in [22]. The optimisation process aims to maximise the margins of compliance with damage stability rules. This empowers maximum flexibility in the subsequent design phases, where the design might be more freely revised while being still compliant with rules. Such a target, along with the early design stage where it is applied, is the main novelty of the present work.

The remainder of the article is organised as follows: first, the new concept of the floodable length according to modern deterministic rules is presented along with the proposed optimisation problem. Then, the methodology is applied to a Compressed Natural Gas (CNG) carrier. The results are discussed by comparison with usual equispaced bulkheads positioning and, finally, conclusions of the study are provided.

2. Materials and Methods

In the present section, first, the revised definition of floodable lengths is provided. Then, the proposed multi-step optimisation process is defined focusing on the optimisation problem solved at each step.

2.1. Floodable Lengths

In the deterministic rules according to SOLAS'90, the concept of floodable length was utilised. The floodable length at a longitudinal position X were defined as the length of the hull FL centred in X and corrected by permeability μ that can be considered lost without submerging the margin line (i.e., a line located 76 mm below the bulkhead deck). The actual floodable length FL is obtained as:

$$FL(X) = \frac{FL_g(X)}{\mu} \tag{1}$$

where FL_g is the geometric floodable length corresponding to the segment of the ship effectively considered lost while evaluating the compliance with damage stability requirements with the lost-buoyancy method.

Current deterministic rules applicable to gas carriers, polar ships or naval vessels are usually more complex. They define box-shaped damage that shall be applied elsewhere along the ship. As a trial subdivision is defined, the standard damage allows the definition of all the possible damage cases involving one or more main watertight compartments. For each damage case, a set of requirements shall be satisfied to assure minimum residual stability after damage.

Recalling these modern deterministic rules, the definition of the former floodable length can be updated as: the length of the hull defined by two subsequent transverse planes, corrected by permeability, that can be considered lost while still fulfilling the damage stability requirements. With this new definition, all the possible feasible locations of main transverse bulkheads can be tested. In detail, given a set of transverse bulkheads, two main cases shall be considered:

- if the length of two adjoining compartments defined by bulkheads located in $[X_i, X_{i+1}, X_{i+2}]$ is larger than the maximum damage length L_d, the sum of the length of the two compartments shall be lower than the floodable length $FL((X_{i+2} - X_i)/2)$.
- if the length of a watertight compartment is lower than L_d, a three-compartment damage case shall be considered including the two adjoining compartments defined by $[X_{i-1}, X_i, X_{i+1}, X_{i+2}]$. Namely, the sum of the length of the three compartments shall be lower than $FL((X_{i+2} - X_{i-1})/2)$.

With similar approaches, the number of adjoining compartments to be considered can be defined. In order to visualise the investigated subdivision, the Wendel diagram can be employed, comparing the triangles spanning over the damaged compartments with the floodable lengths corrected with permeability.

2.2. Multistep Optimisation Process

The overall process is provided in Figure 1. First, the number of watertight bulkheads N shall be defined. Then, the initial set of fixed bulkheads shall be initialised with at least the position of the first and the last one, i.e., the longitudinal position of the ship's stern and bow, respectively. The remaining free $n = N - 2$ bulkheads can be initially located to assure equal spacing within them. The free bulkheads' longitudinal positions are considered the n variables for the optimisation problem, thoroughly described in Section 2.3.

The optimal positions of the free bulkheads are determined to maximise the margin M between the floodable lengths and actual flooded lengths for each set of damage cases assessed according to the applicable maximum damage length L_d. Since the number of considered margins can be defined as equal to the number of considered damage cases, the maximisation can be granted only to the minimum margin.

However, this margin is defined only by the two bulkheads defining the extent of the so-called critical damage case, namely the critical bulkheads. Thus, infinite solutions still exist regarding the positions of the remaining free bulkheads. In fact, their position does not influence the minimum margin, which is only determined by the critical bulkheads. This is why the multi-step approach has been introduced: at each iteration, the fixed bulkheads' set is updated adding the position of the two critical bulkheads. Hence, the optimisation problem dimension is reduced after each step of 2 if both critical bulkheads are free or 1 if one is free and one is already fixed.

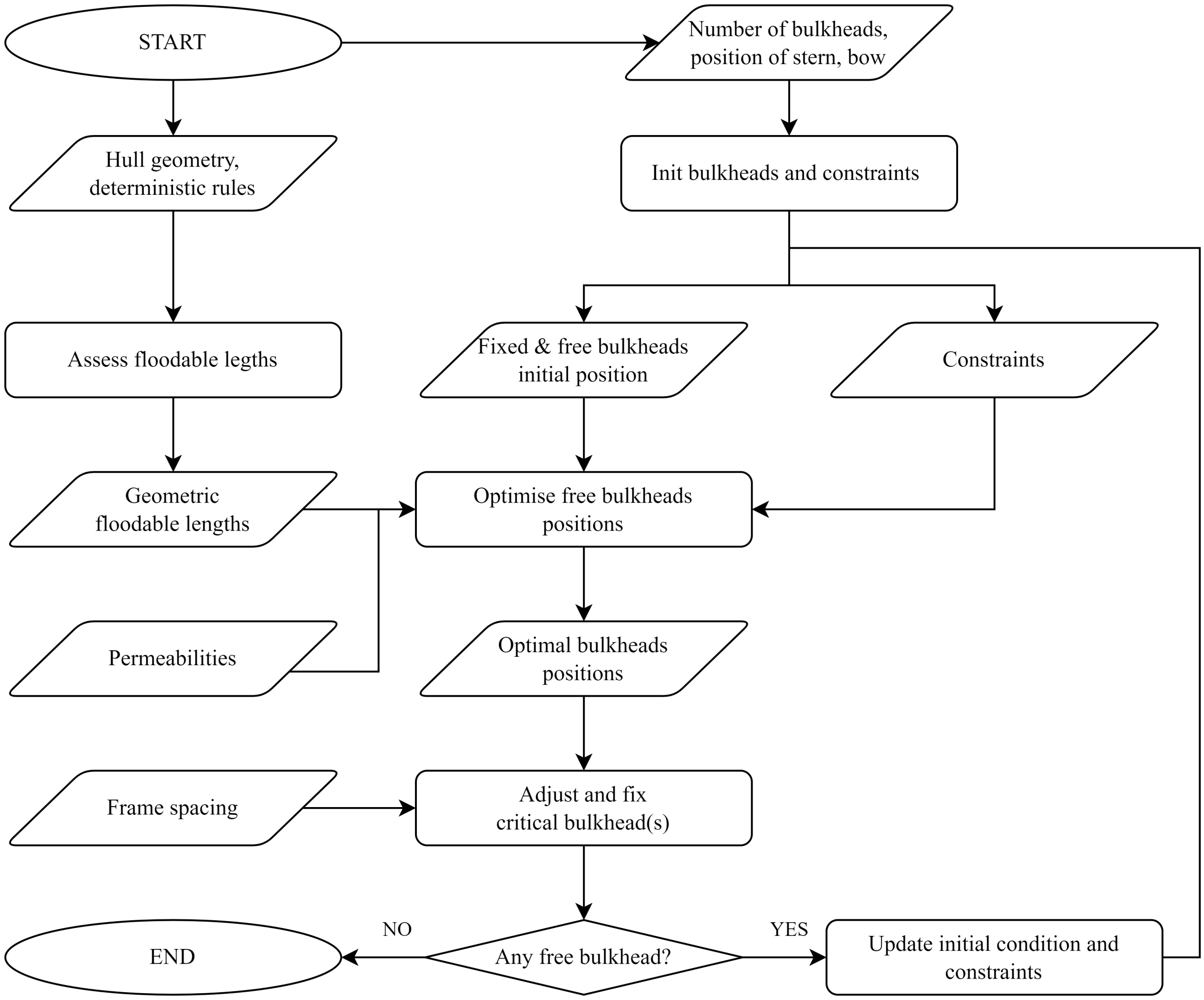

Figure 1. Applied multi-step optimisation process.

Furthermore, before updating the fixed bulkheads set with the critical bulkhead(s), their position shall be adjusted. The position of each critical bulkhead shall be moved to a web frame location, in order to assure the structural consistency of the optimised subdivision with the frame system. If only one critical bulkhead is free, two options shall be analysed. Namely, given x_c the position of the free critical bulkhead and L_f the web frame spacing, the two locations to be analysed are:

$$x_1 = L_f \cdot \text{floor}\left(\frac{x_c}{L_f}\right) \quad x_2 = L_f \cdot \text{ceil}\left(\frac{x_c}{L_f}\right) \tag{2}$$

If both the critical bulkheads are free (x_{c_1}, x_{c_2}), four cases shall be considered:

$$[x_{11}, x_{21}] \quad [x_{11}, x_{22}] \quad [x_{21}, x_{21}] \quad [x_{21}, x_{22}] \tag{3}$$

where:

$$x_{i1} = L_f \cdot \text{floor}\left(\frac{x_{c_i}}{L_f}\right) \quad x_{i2} = L_f \cdot \text{ceil}\left(\frac{x_{c_i}}{L_f}\right) \tag{4}$$

Among these options, the solution shall be chosen which minimises the objective function defined in the next section. Once the critical bulkhead position is adjusted and fixed, the optimisation process is repeated starting from the position of the free bulkheads defined in the previous iteration.

The iterations are repeated until the last free bulkhead's position has been fixed. Thus, the proposed multi-step approach can assure to maximise not only the first critical margin but also the position of all the remaining free bulkheads although they will lead to margins greater than the minimum.

2.3. Optimisation Problem

Two vectors/sets can be defined to characterise the optimisation problem at a generic step: a $N \times 1$ vector $\mathbf{X}$ containing the longitudinal positions of all the transverse bulkheads (fixed and free) in ascending order:

$$\mathbf{X} = [X_1, \ldots, X_N] \tag{5}$$

a $n \times 1$ vector $\mathbf{x} \subset \mathbf{X}$ containing the longitudinal position of free bulkheads only:

$$\mathbf{x} = [x_1, \ldots, x_n] \tag{6}$$

X_1 and X_N shall be considered fixed and stands for the aft and fore extremes of the ship, respectively. Hence, $n \leq N - 2$ at each step. The elements of the vector $\mathbf{x}$ are the variables of the optimisation problem. During the optimisation, the consistency of the position of free bulkheads in $\mathbf{X}$ and $\mathbf{x}$ shall be always ensured.

Considering the case of two adjoining compartments simultaneously flooded, $N - 2$ actual flooded lengths $L(X_{M_i})$ can be defined as:

$$L(X_{M_i}) = X_{i+2} - X_i \tag{7}$$

where X_{M_i} is the centre of the actual flooded length L spanning over the two adjoining compartments, which is defined as:

$$X_{M_i} = \frac{X_i + X_{i+2}}{2} \tag{8}$$

At these positions the floodable length $FL(X_{M_i})$ can be also evaluated from the floodable lengths curve. Therefore, and $N - 2$ margins vector $\mathbf{M}$, can be defined as:

$$M_i = FL(X_{M_i}) - L(X_{M_i}) \tag{9}$$

The vector $\mathbf{M}$ represents the degree of satisfaction of damage stability requirements according to the considered deterministic rules: a non-negative value of M_i stands for compliance with rules requirements of the damage case comprising i-th and $i - 1$-th compartments.

2.3.1. Objective Function

As mentioned, the objective of the optimisation carried out at each step is to maximise the degree of satisfaction with damage stability rules. This objective can be reached by minimising the inverse of the minimum value of the margins vector. However, couples of compartments delimited by two fixed bulkheads shall be not considered, since are not affected by the variables $\mathbf{x}$ of the optimisation problem. Thus, the objective function can be defined as:

$$obj = -\min(\mathbf{o}) \tag{10}$$

where $\mathbf{o}$ is an $m \times 1$ vector:

$$\mathbf{o} = \{M_i \in \mathbf{M} \mid X_i \in \mathbf{x} \vee X_{i+2} \in \mathbf{x}\} \tag{11}$$

with $m \leq N - 2$.

2.3.2. Constraints

To ensure compliance with rules, it is essential to prevent negative values of margins **m**. This can be assured by defining a set of inequality constraints $\mathbf{g}_r$ applicable to each couple of adjoining compartments delimited at least by a free bulkhead:

$$\mathbf{g}_r = \left\{ \text{for} \quad i = 1, ..., N-2 \quad \text{if} \quad X_i \in \mathbf{x} \vee X_{i+2} \in \mathbf{x} \qquad g_{r_j} \quad : \quad -M_i \right. \tag{12}$$

Besides, three-flooded room damage cases shall be avoided. To this end, the length of each compartment shall be greater than the maximum damage length L_d according to considered deterministic rules. Furthermore, for each compartment, a minimum and maximum length can be imposed due to the dimensions of the main machinery or to avoid structural issues. These conditions can be guaranteed by defining another set of inequality constraints $\mathbf{g}_l$ applicable to each compartment delimited at least by a free bulkhead:

$$\mathbf{g}_l = \begin{cases} \text{for} \quad i = 1, ..., N-1 \quad \text{if} \quad X_i \in \mathbf{x} \vee X_{i+1} \in \mathbf{x} \qquad g_{l_j} \quad : \quad X_i - X_{i+1} + \max\left(L_{min_i},\ L_d\right) \\ \text{for} \quad i = 1, ..., N-1 \quad \text{if} \quad X_i \in \mathbf{x} \vee X_{i+1} \in \mathbf{x} \qquad g_{l_{2j}} \quad : \quad X_{i+1} - X_i - L_{max_i} \end{cases} \tag{13}$$

where $\mathbf{L}_{min}$ and $\mathbf{L}_{max}$ are two $N-1 \times 1$ vectors containing the minimum and maximum length for each watertight compartment of the ship.

2.3.3. Optimisation Model

Therefore, the optimal position of the n free bulkheads can be established by solving the following optimisation problem:

$$\begin{cases} \text{find} & \mathbf{x} \\ \text{minimise} & obj = -\min(\mathbf{o}) \\ \text{subject to} & \mathbf{g}^T = [\mathbf{g}_r,\ \mathbf{g}_l]^T \leq 0 \end{cases} \tag{14}$$

The problem is here solved by applying a hybrid interior-point method combining a line search method with a trust region method to achieve fast and robust convergence for non-linear programming problems [23–25]. The line search method computes steps by factoring the primal-dual equations and is well-suited for handling non-linearities and non-convexities. The trust region method, on the other hand, uses a conjugate gradient iteration and is effective in dealing with ill-conditioned or singular linear systems. The algorithm is designed to automatically switch between these two methods as needed, making use of the strengths of each while overcoming their limitations.

The line search method is used as the primary step-computing strategy and is tried first at each iteration. If the line search method fails to produce a step that satisfies the primal-dual feasibility and optimality conditions, the algorithm automatically invokes the trust region method, which is guaranteed to make progress toward stationarity. The algorithm continues alternating between the two methods until convergence is achieved.

3. Application

In the present section, the proposed methodology is applied to a peculiar ship type subject to deterministic stability criteria: a CNG ship. Considering that, currently, CNG ships cover just a niche of the Natural Gas (NG) transport sector, first the CNG carrier is introduced along with the applied deterministic rules for damage stability coming from IGC. Then, several main transverse subdivision options are defined and analysed by applying a different number of bulkheads dividing the main cargo holds.

3.1. CNG Ship Layout

NG demand has constantly risen in the last decades [26]and forecasts prolong the growth in the near future [27]. The recent events, especially the war between Russia and Ukraine, are causing a reduction of NG flows through land-based pipelines from Russia to Western Europe countries [28,29]. Therefore, the demand for shipborne transport of NG from other sources to Western Europe is rising creating new opportunities for the maritime industry besides consolidated markets such as Japan, China, Republic of Korea, etc.

In this context, among the technologies for NG maritime transportation, the CNG technology is a viable solution being more profitable than Liquefied Natural Gas (LNG) or submarine pipelines for long-medium distances (for instance from East-Med gas fields to Italy) [30,31]. Although CNG has about half the volumetric reduction rate than LNG, it does not require the costly on-shore infrastructures for liquefaction and regasification, but only two single piers equipped for loading and offloading [32].

The typical layout of a CNG vessel as adopted in the present work is provided in Figure 2. In the aft body of the ship, two compartments are fitted to allocate the Pod propulsors and the main engine room to accommodate dual-fuel diesel generators. In the forebody, abaft the collision bulkhead, a compartment is fitted for the Submerged Turret Loading (STL) system, which enables ship mooring at a buoy to load and unload cargo. Above the recess required by STL the booster compressors for cargo loading are fitted. The length of these compartments shall be kept as small as possible, thus it has been here assessed according to the dimensions of the main machinery and related clearances and considered fixed.

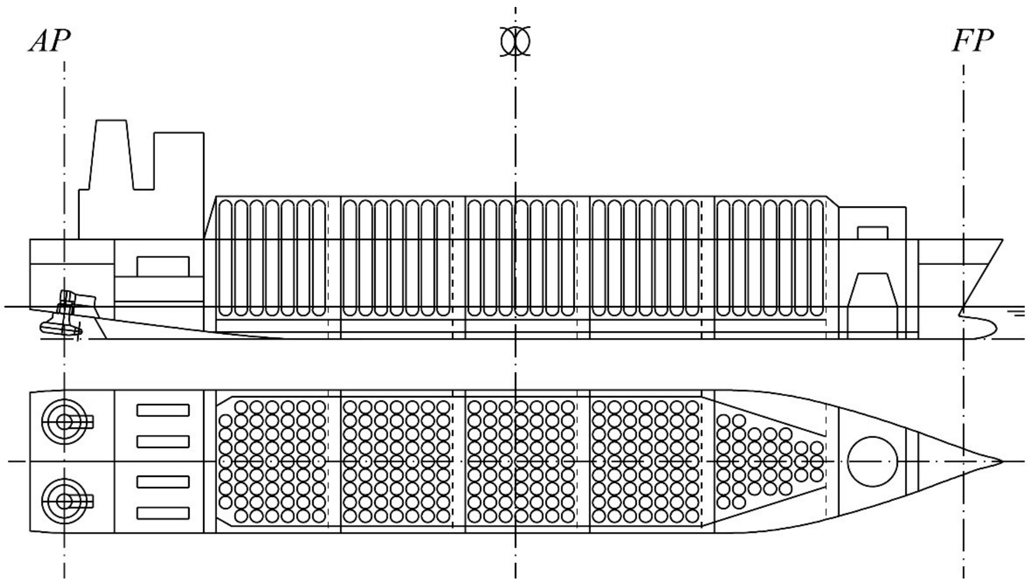

Figure 2. Typical layout of a podded CNG ship with STL system.

Between the previously described aft and fore compartments, the main cargo holds are fitted. Within them, Pressure Vessels (PV) containing CNG are positioned in a vertical position. To assure a sufficient length of the PV, an open-deck midship section has been here adopted. The PV are enclosed within a non-structural dome. Several technologies are available for PV construction. According to ISO, four categories can be defined due to adopted materials [33]:

- Type I: all-metal;
- Type II: hoop-wrapped, metal liner reinforced with resin-impregnated continuous filament;
- Type III: fully-wrapped, metal liner reinforced with resin-impregnated continuous filament;
- Type IV: all-composite, resin-impregnated continuous filament with a non-metallic liner.

When Type III or IV PV are adopted, due to low-density containment system and cargo, the need to rise the ship's height of centre of gravity *KG* was deemed necessary to reduce accelerations in rough sea [20]. Thus a double-double bottom has been introduced beneath the cargo holds, leading also to an increase in the surface available to install PV foundations.

Regarding the PV's arrangement within each cargo hold, class societies issued regulations that affect the framing system and internal subdivision of the CNG ship [34,35]. In detail, rules require in the cargo holds area a double bottom and a double hull: 760 mm for ABS, $\min(B/15, 2\ \text{m})$ for DNV-GL. Besides, they define a minimum distance among subsequent PV's rows and between vessels and bulkheads/sides to enable inspection and maintenance. Finally, a cofferdam shall be fitted between cargo holds and other main compartments as well as between two adjoining cargo holds. Although cofferdams are not effective in damage stability calculations, for each bulkhead fitted in cargo space, an entire row of PV is lost. Hence, choosing the wrong number of bulkheads, ship capacity is reduced and the specific vessel design is seriously penalised in the framework of MADM methods.

3.2. Damage Stability Criteria

As mentioned, deterministic damage stability requirements lead to the novel definition of floodable lengths. Considering a CNG ship, IGC defines the subdivision peculiarities, standard damages and damage stability criteria.

First of all, the IGC defines which bulkheads shall be considered effective in damage stability calculations. Namely, only the transverse bulkheads located at a longitudinal distance larger than the standard damage length L_d can be considered in calculations. The applied standard damages are reported in Table 1. Therefore, neither all the cofferdam's bulkheads nor damage cases involving three or more adjoining compartments shall be considered for CNG ship damage stability assessment.

Table 1. Standard damage definition according to IGC code.

	Extent (m)		
Damage Type	**Longitudinal**	**Transverse**	**Vertical**
Side	$\min\left(\frac{1}{3}L^{2/3}, 14.5\right)$	$\min\left(\frac{1}{5}B, 11.5\right)$	no limitations
Bottom ($x < 0.7\ L$)	$\min\left(\frac{1}{3}L^{2/3}, 14.5\right)$	$\min\left(\frac{1}{6}B, 5.0\right)$	$\min\left(\frac{1}{15}B, 2.0\right)$
Bottom (elsewhere)	$\min\left(\frac{1}{3}L^{2/3}, 14.5\right)$	$\min\left(\frac{1}{6}B, 10.0\right)$	$\min\left(\frac{1}{15}B, 2.0\right)$

The ship is required to withstand the standard damages applied elsewhere as well as any smaller damage having more severe consequences with sufficient residual stability. Residual stability is deemed sufficient if the following damage stability requirements are met at the final stage of flooding:

- the righting arm curve of the damaged ship shall have a minimum positive range of 20 deg;
- the maximum residual lever within the 20 deg positive range shall be at least 0.1 m;
- the area under righting arm curve of the damaged ship within the 20 deg positive range shall be at least 0.0175 m rad.

The 20 deg positive range can be measured from any angle commencing between the equilibrium position and the angle of 25 deg or 30 deg whether the deck is not submerged.

Besides, requirements for intermediate flooding stages are also defined in the IGC. Namely, no unprotected openings shall be submerged and the heel angle shall not exceed 30 deg. Moreover, the code states that, in intermediate flooding stages, the residual stability should not be significantly lower than the one required at the final stage. Currently, no explanation of what "significantly" means in terms of quantities is provided in IGC. This is why, here, only the final stage requirements have been considered for the determination of floodable lengths.

3.3. Test Ship

In the present study, a CNG ship has been used to test the proposed subdivision optimisation process. The main particulars of the ship are reported in Table 2. The lines plan of the ship is provided in Figure 3.

Table 2. Main particulars of the test ship.

Name	Sym.	Value	
Length at Waterline	L_{WL}	223.000	m
Breadth	B	36.680	m
Draught	T	8.071	m
Depth	D	25.000	m
Displacement	Δ	47904	t
Height of centre of gravity	KG	14.53	m
Centre of buoyancy	LCB	106.480	m
Centre of buoyancy	lcb	−2.250	%
Block coefficient	C_B	0.708	
Length on Breadth	L/B	6.080	
Breadth on Draught	B/T	4.545	
Depth on Draught	D/T	3.098	

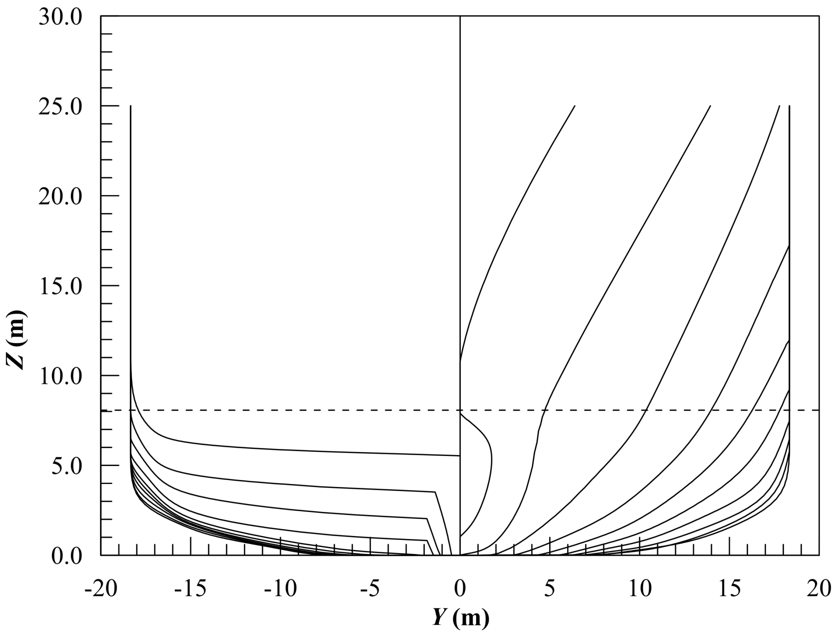

Figure 3. Body plan of the test CNG ship.

The ship utilises Type III PV that have a diameter of 2.54 m. Applying class rules, the distance between subsequent rows of vessels is 0.6 m. It is supposed that a web frame is located below each row of PV in the cargo spaces. Thus, the adopted web frame spacing is $L_f = 3.14$ m. Besides, in order to avoid the generation of compartments having too short lengths, a constant minimum length $L_{min} = 7 \cdot L_f$ has been applied to all cargo holds.

As mentioned, the dimension of the first two compartments hosting steering and engine rooms, respectively, and the last two, hosting STL system, compressors, fore peak and mooring space, are fixed. Hence, given n as the number of free bulkheads within the cargo space, the **X** e **x** are initialised as follows:

$$\mathbf{X} = [-7, 15.7, 37.68, \mathbf{x}, 191.54, 213.52, 230.33] \quad \mathbf{x} = [37.68 + i \cdot \tfrac{191.54-37.68}{n+1}] \tag{15}$$

with $i = [1, ..., n]$.

4. Results

In the present section, the results for the bulkheads' position optimisation for the test CNG ship are given. First, the floodable lengths are computed and then the optimisation results are provided.

4.1. Floodable Lengths

Table 3 provides the assumed permeabilities for the computation of actual floodable lengths according to Equation (1). Figure 4 shows the geometric and actual floodable lengths computed according to the IGC.

Table 3. Standard permeabilities assumed by SOLAS and their application.

Space type	Permeability	Application
Stores	0.60	Cargo holds
Accomodations	0.95	n.a.
Machinery	0.85	Aft machinery rooms, Engine room, STL space
Void spaces	0.95	Afore collision bulkhead
Liquids	0 or 0.95	Side tanks and double bottom

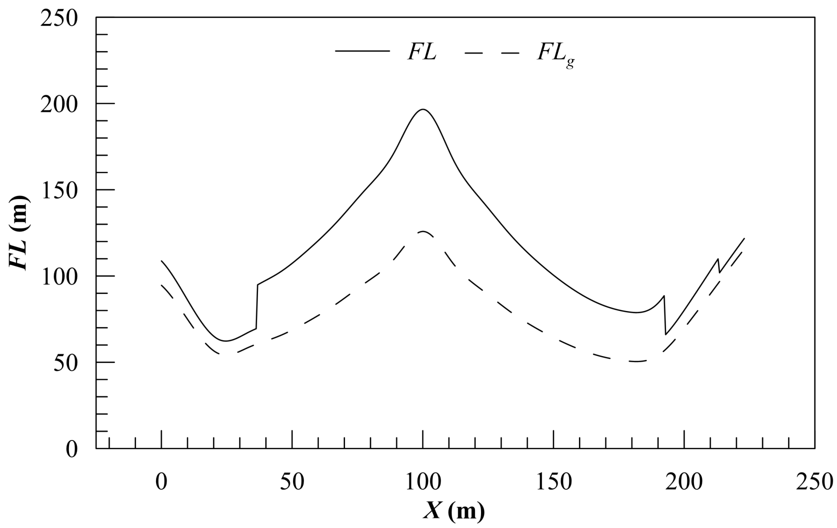

Figure 4. Geometric and corrected floodable length for the test ship.

4.2. Optimised Bulkheads' Position

Table 4 as well as Figures 5–7 shows the results of the optimisation of cargo holds' bulkheads position, considering 2, 3, and 4 cargo holds cases. More details about the calculation process, focusing on the 4 cargo holds case, are given in Appendix A. It is worth noticing that in all three cases the subdivision is found feasible, although the 2 cargo holds case entails only marginal compliance with rules. Table 5 reports the floodable lengths, actual flooded lengths and margins obtained solving the optimisation problem in the three cases.

Table 4. Position of the bulkheads obtained through optimisation process.

bh		*X* (m)	
	2 Cargo Holds	3 Cargo Holds	4 Cargo Holds
0	−7.00	−7.00	−7.00
1	15.70	15.70	15.70
2	37.68	37.68	37.68
3	169.56	128.74	59.66
4	191.54	169.56	147.58
5	213.52	191.54	169.56
6	230.33	213.52	191.54
7		230.33	213.52
8			230.33

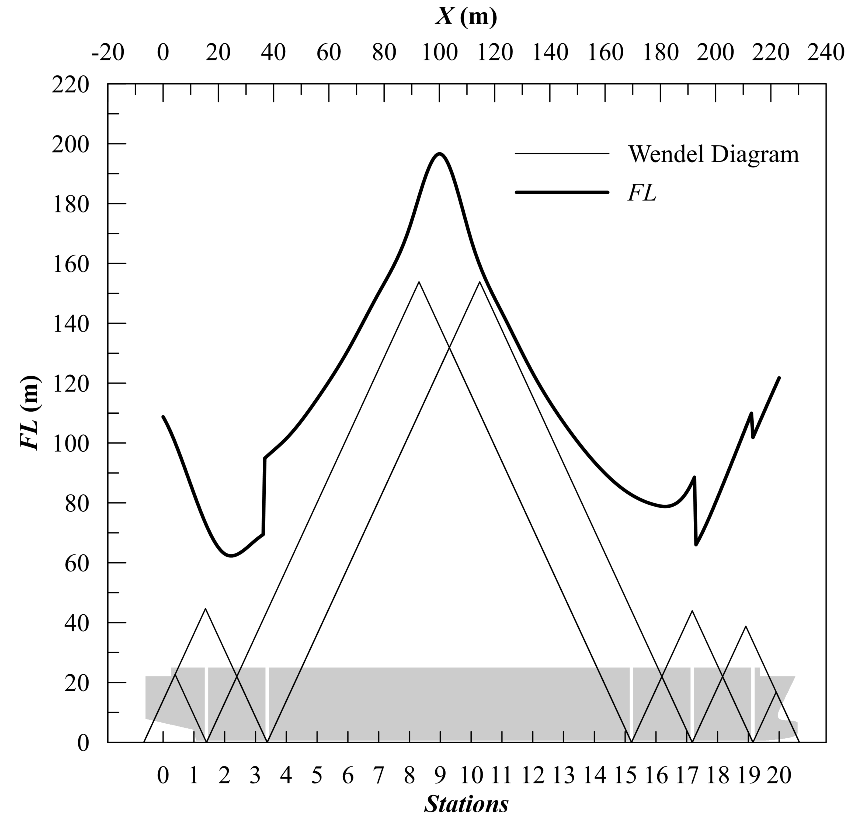

Figure 5. Optimised subdivision: 2 cargo hold case.

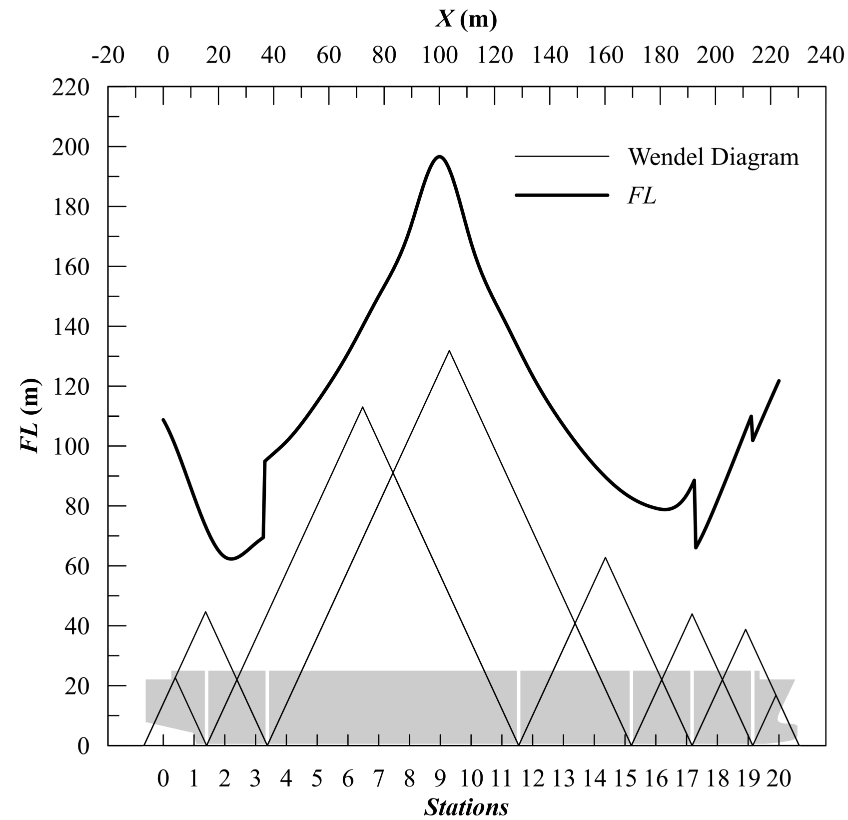

Figure 6. Optimised subdivision: 3 cargo hold case.

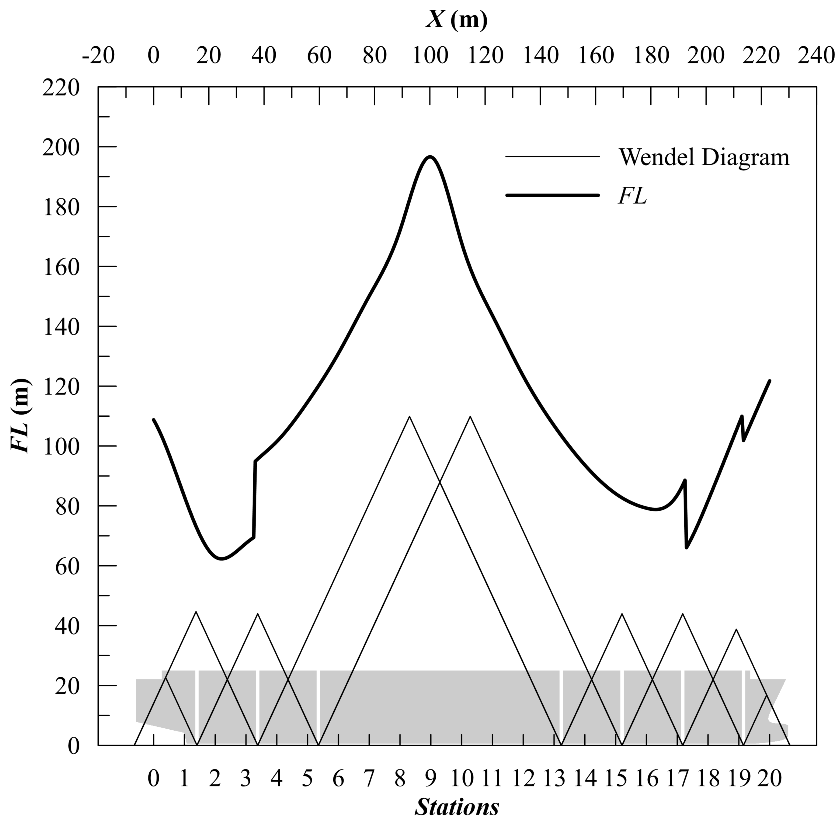

Figure 7. Optimised subdivision: 4 cargo hold case.

Table 5. Results of the optimisation process

Cases	Quantity	Unit	bhs 0-2	bhs 1-3	bhs 2-4	bhs 3-5	bhs 4-6	bhs 5-7	bhs 6-8
2 cargo holds	X_M	m	15.34	92.63	114.61	191.54	210.94		
	L	m	44.68	153.86	153.86	43.96	38.79		
	FL	m	73.19	182.28	159.44	86.29	105.20		
	M	m	28.51	28.42	5.58	42.33	66.41		
3 cargo holds	X_M	m	15.34	72.22	103.62	160.14	191.54	210.94	
	L	m	44.68	113.04	131.88	62.80	43.96	38.79	
	FL	m	73.19	140.04	192.38	89.70	86.29	105.20	
	M	m	28.51	27.00	60.50	26.90	42.33	66.41	
4 cargo holds	X_M	m	15.34	37.68	92.63	114.61	169.56	191.54	210.94
	L	m	44.68	43.96	109.90	109.90	43.96	43.96	38.79
	FL	m	73.19	95.07	182.28	159.44	82.70	86.29	105.20
	M	m	28.51	51.11	72.38	49.54	38.74	42.33	66.41

5. Discussion

In order to show the benefits of the proposed multi-step optimisation process, the results coming from conventional cargo hold subdivision patterns are presented, namely the fitting of equispaced bulkheads dividing cargo holds. Figures 8–10 along with Table 6 shows the results coming from a non-optimised procedure where the same length is given to 2, 3 and 4 cargo holds.

The equispaced pattern lead always to lower margins. For the 4 cargo holds case, the minimum margin linked to free bulkheads decreases from 38.7 m to 18.5 m (52% reduction); for the 3 cargo holds case, from 26.9 m to 6.4 m (76% reduction); for the 2 cargo holds case, the single bulkhead located at a half-length of the cargo space is not compliant with rules: namely, a negative margin is found considering lost the two compartments bounded by bulkheads 3 and 5.

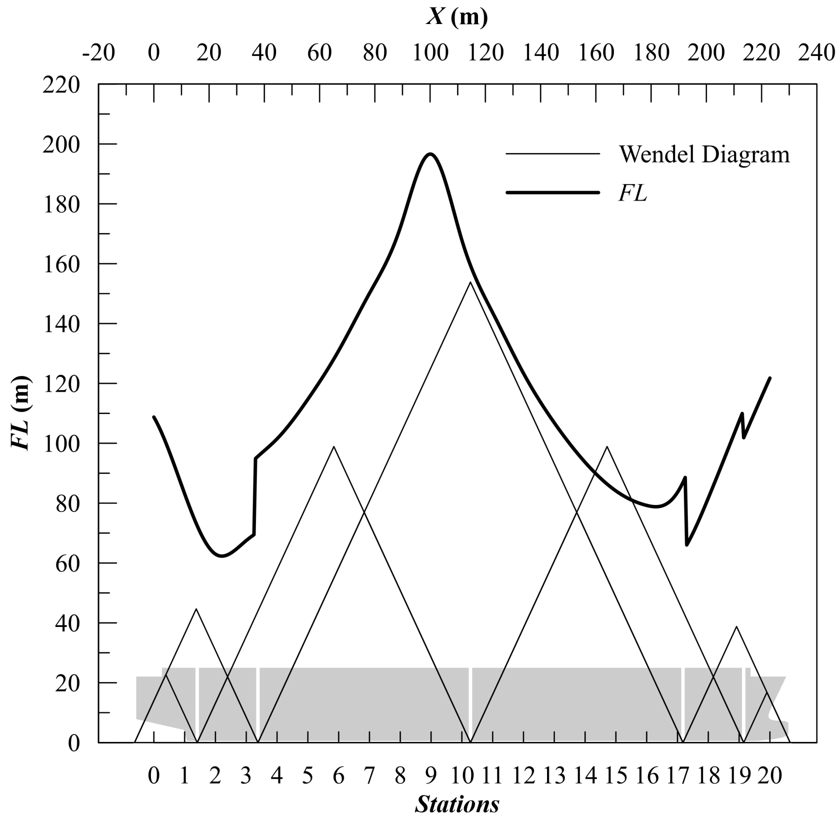

Figure 8. Equispaced subdivision: 2 cargo hold case.

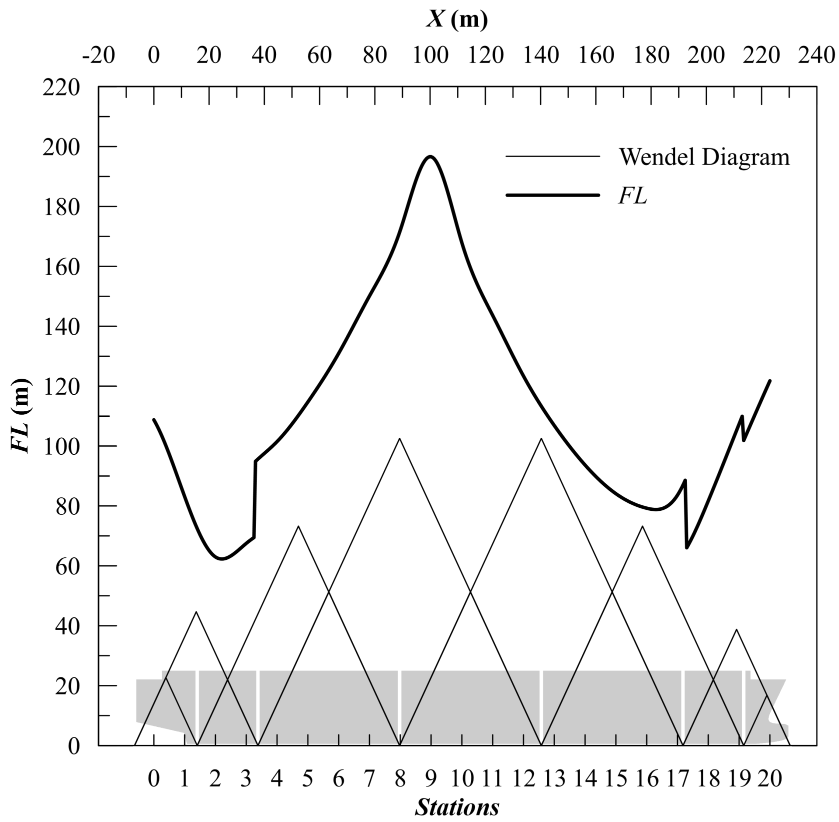

Figure 9. Equispaced subdivision: 3 cargo hold case.

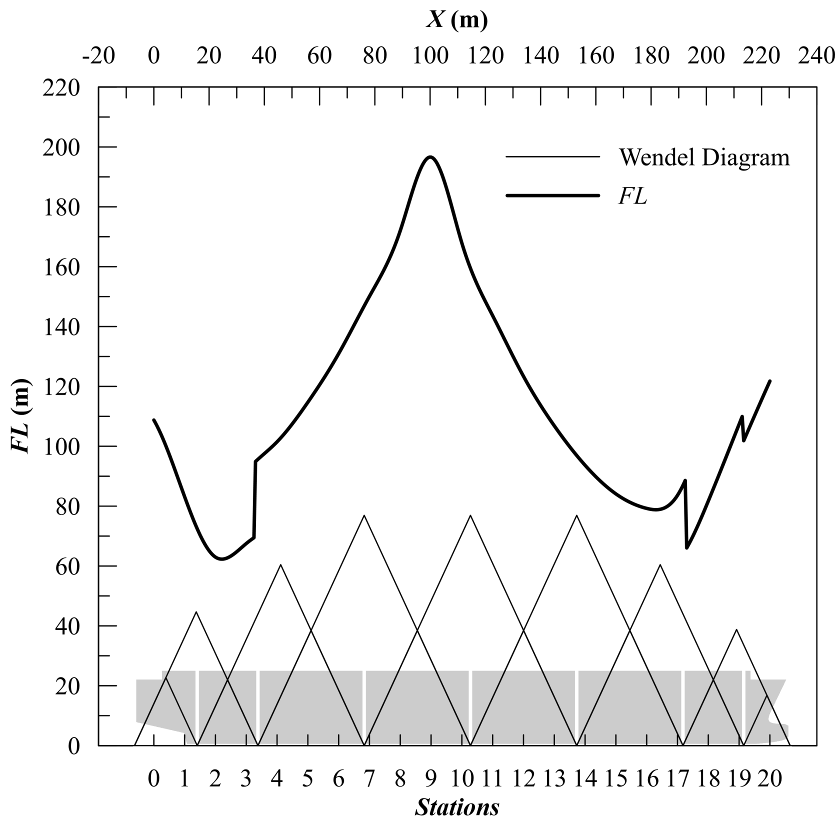

Figure 10. Equispaced subdivision: 4 cargo hold case.

Table 6. Results of the equispaced bulkheads cases.

Cases	Quantity	Unit	bhs 0-2	bhs 1-3	bhs 2-4	bhs 3-5	bhs 4-6	bhs 5-7	bhs 6-8
2 cargo holds	X_M	m	15.34	65.16	114.61	164.07	210.94		
	L	m	44.68	98.91	153.86	98.91	38.79		
	FL	m	73.19	128.17	159.44	86.37	105.20		
	M	m	28.51	29.26	5.58	−12.54	66.41		
3 cargo holds	X_M	m	15.34	52.33	88.97	140.25	176.89	210.94	
	L	m	44.68	73.27	102.57	102.57	73.27	38.79	
	FL	m	73.19	110.25	171.40	113.31	79.63	105.20	
	M	m	28.51	36.98	68.83	10.73	6.37	66.41	
4 cargo holds	X_M	m	15.34	45.92	76.15	114.61	153.08	183.30	210.94
	L	m	44.68	60.45	76.93	76.93	76.93	60.45	38.79
	FL	m	73.19	102.80	146.88	159.44	96.92	78.95	105.20
	M	m	28.51	42.35	69.95	82.51	19.99	18.50	66.41

These results highlight two main achievements of the optimisation procedure. First, the process makes it possible to properly identify the minimum number of bulkheads within the cargo space. In the studied design, a single bulkhead properly placed can be deemed sufficient. Recalling that for each bulkhead an entire row of PV shall be removed to fit the cofferdam, a limitation of the number of cargo holds can improve the ship capacity although a careful balance of weights and centre of mass shall be ensured. In a MADM environment, this process can be easily handled by adjusting the first estimation of mass centre and weight breakdown by considering the outcome of bulkheads' position optimisation.

The second advantage is the maximisation of margins. This process widens the freedom of the next design stages where design changes might be necessary to meet all the design requirements. In fact, at a concept design stage, most of the quantities are somehow uncertain. For instance, weight breakdown and mass centre height are usually defined with a 5% allowance. The proposed process helps in refining the weight breakdown through a more precise computation of the contributions coming from the NG containment system, cargo and bulkheads/cofferdams. Moreover, the more accurate position of PV and bulkheads leads to an easier estimation of the longitudinal equilibrium of the ship to assure the upright position of the analysed design alternative.

Finally, in the cases with 2 and 4 bulkheads, the optimisation process generates compartments having the minimum length defined by constraints. Hence, the constraints shall be defined carefully and shall consider multiple aspects, in particular ship structure feasibility. The present work mainly focused on the definition of the multi-step procedure, leaving aside the structural issues connected with irregular, too-long or too-short cargo holds. Nevertheless, these aspects can be handled by refining the constraints definition.

Furthermore, here, only the positions of bulkheads dividing cargo holds have been optimised since the test ship is a cargo ship. Thus, in order to maximise the cargo capacity, the technical spaces shall be always kept as small as possible. For other types of ships under deterministic rules, such as icebreakers or naval ships, a larger number of free bulkheads is envisaged. Apart from aft and stern boundaries, all the other bulkheads' positions can be optimised. In such cases, however, more complex length constraints shall be defined, mainly driven by main machinery dimensions and rules (e.g., position of collision bulkhead) and further attention is required on the longitudinal equilibrium. Namely, a heavy longitudinal translation might require to be compensated with a translation of the longitudinal centre of buoyancy. This affects also the shape of the floodable lengths which has been proved to be influenced by LCB position [22].

6. Conclusions

In the present study, a methodology for optimising the position of bulkheads in the early design stages of ships under deterministic damage stability requirements has been successfully tested. The technique is able to deal with multiple bulkheads through a multi-stage optimization procedure and a progressive reduction in the dimension of the optimisation problem, i.e., a reduction in the number of free bulkheads. The tests on a CNG ship have shown how the methodology can be utilised to minimise the number of bulkheads and ensure the highest possible flexibility and freedom of modification in the next design phases.

The key of the proposed technique stands in a new definition of the floodable lengths, which were calculated here according to the deterministic requirements from IGC. In this study, a direct calculation of floodable lengths has been carried out. However, metamodels can be used instead to predict the floodable lengths prior to defining the hull forms. This can facilitate integration within concept design mathematical models based on MADM, which rely on Monte Carlo sampling to generate design alternatives and usually define ship geometry in terms of main hull dimensions and coefficients only.

Further work is still required to better define the length constraints. These are essential to easily handle the structural issues that might arise from an irregular main watertight subdivision. Proper meta-models could be developed to define the maximum/minimum lengths of the main watertight compartments. Moreover, they are also required to deal with machinery and auxiliary spaces typical of ship types under deterministic rules other than CNG vessels, which are subject to deterministic rules. Finally, the procedure could be improved by considering longitudinal equilibrium and thus recalculating the floodable lengths as a function of displacement and the position of the centre of buoyancy.

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Abbreviations

The following abbreviations are used in this manuscript:

B	Ship breadth
CNG	Compressed Natural Gas
FL	Floodable length (m)
FL_g	Geometric floodable length (m)
$\mathbf{g}$	Inequality constraints
IGC	International Gas Code
ISO	International Organization for Standardization
KG	Height of the centre of gravity (m)
L	Actual flooded length (m)
L_d	Maximum damage length (m)
L_f	Web frame spacing (m)
L_{max_i}	Maximum length of the *i*-th compartment
L_{min_i}	Minimum length of the *i*-th compartment
LNG	Liquefied Natural Gas
L_r	Ship length according to IGC (m)
M_i	*i*-th margin (m)
m	Number of margins related to the free bulkheads only (-)
MADM	Multi-Attribute Decision Making
MODM	Multi-Objective Decision Making
N	Total number of transverse bulkheads (-)
NG	Natural Gas
n	Number of free bulkheads (-)
o_i	*i*-th margin related to the free bulkheads only (m)
PV	Pressure Vessels
SOLAS	International Convention for the Safety Of Life At Sea
STL	Submerged Turret Loading
X_i	Longitudinal position of *i*-th transverse bulkhead (m)
X_{M_i}	Longitudinal position of the centre of *i*-th actual flooded length (m)
x_{c_i}	Longitudinal position of *i*-th critical bulkhead (m)
x_i	Longitudinal position of *i*-th free bulkhead (m)
μ	Permeability (-)

Appendix A. Worked Example

In the present appendix a worked example is provided related to the 4 cargo holds case. The proposed process is described step by step highlighting how the algorithm defines the final position of the bulkheads. The appendix aims to ease the comprehension of the paper and the reproduction of its results.

Appendix A.1. Initialisation

The 4 cargo holds optimisation problem involves 6 fixed bulkheads and 3 free bulkheads, which are initially assumed to be equispaced:

$$\mathbf{X} = [-7, 15.7, 37.68, 76.145, 114.61, 153.075, 191.54, 213.52, 230.33] \tag{A1}$$

$$\mathbf{x} = [76.145, 114.61, 153.075] \tag{A2}$$

Appendix A.2. Step 1

In the first step, the optimisation problem has size 3. The solution of the optimization problem gives the following position of the free bulkheads:

$$\mathbf{x} = [76.059, 147.579, 169.56] \tag{A3}$$

The two critical bulkheads are located at $X = 147.579$ and $X = 191.54$ corresponding to a margin $M = 38.735$. Since one bulkhead is fixed, the single bulkhead adjustment procedure is invoked on the free bulkhead located at $X = 147.579$, leading to the following adjusted position:

$$\mathbf{x} = [76.059, 147.58, 169.56] \tag{A4}$$

The critical bulkhead is fixed defining the starting point for step 2:

$$\mathbf{X} = [-7, 15.7, 37.68, 76.059, 147.58, 169.56, 191.54, 213.52, 230.33] \tag{A5}$$

$$\mathbf{x} = [76.059, 169.56] \tag{A6}$$

Appendix A.3. Step 2

In the second step, the optimisation problem has size 2. The solution of the optimization problem gives the following position of the free bulkheads:

$$\mathbf{x} = [62.940, 169.56] \tag{A7}$$

The two critical bulkheads are located at $X = 169.56$ and $X = 213.52$ corresponding to a margin $M = 42.3346$. Again one bulkhead is fixed, hence the single bulkhead adjustment procedure is invoked on the free bulkhead located at $X = 169.56$. In this case, due to length constraints, the bulkhead is already located on a web frame. Thus, the adjustment result does not change the bulkhead position:

$$\mathbf{x} = [62.94, 169.56] \tag{A8}$$

The critical bulkhead is fixed defining the starting point for step 3:

$$\mathbf{X} = [-7, 15.7, 37.68, 62.94, 147.58, 169.56, 191.54, 213.52, 230.33] \tag{A9}$$

$$\mathbf{x} = [62.94] \tag{A10}$$

Appendix A.4. Step 3

In the third step, the optimisation problem has size 1. The solution of the optimization problem gives the following position of the free bulkheads:

$$\mathbf{x} = [59.66] \tag{A11}$$

The two critical bulkheads are located at $X = 59.66$ and $X = 169.56$ corresponding to a margin $M = 49.5394$. Since there is only one free bulkhead, the single bulkhead adjustment procedure is invoked on it. Again, due to length constraints, the bulkhead is already located on a web frame. Thus, the adjustment result does not change the bulkhead position:

$$\mathbf{x} = [59.66] \tag{A12}$$

The critical bulkhead is fixed. Since there are no more free bulkheads the final solution of the multi-step problem is reached:

$$\mathbf{X} = [-7, 15.7, 37.68, 59.66, 147.58, 169.56, 191.54, 213.52, 230.33] \quad \text{(A13)}$$

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