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Application of the IMO Second Generation Intact Stability Criteria to a Ballast-Free Containership

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Abstract: A methodology is presented to systematically modify the hull shape of a ballast-free container ship, in order to manage the issue of righting lever variation in waves. The IMO second generation intact stability criteria have been identified as a stability performance assessment tool, while the vertical prismatic coefficient has been selected as the leading parameter of hull modifications to carry out the sensitivity analysis. A revised Lackenby procedure has been chosen to make systematic changes at the hull form. The outcomes of this investigation point out that the proposed procedure is suitable to enable the ship to be fully compliant with the IMO vulnerability levels with minor design adjustment.

Keywords: second generation intact stability criteria; containership; pure loss of stability; parametric rolling; systematic hull variation; innovative ship design

Citation: Petacco, N.; Pitardi, D.; Podenzana Bonvino, C.; Gualeni, P. Application of the IMO Second Generation Intact Stability Criteria to a Ballast-Free Containership. *J. Mar. Sci. Eng.* **2021**, *9*, 1416. <https://doi.org/10.3390/jmse9121416>

Academic Editor: Md Jahir Rizvi

Received: 7 November 2021

Accepted: 9 December 2021

Published: 11 December 2021

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1. Introduction

In this paper, a *ballast-free* containership has been selected for an “intact stability in waves” investigation. The ship is assessed according to the Second Generation Intact Stability criteria (SGISc) as defined in [1]. With the term *ballast-free* we mean a ship which has no need to add or discharge ballast during the loading/unloading operations. The amount of ballast water on board is in fact kept constant and properly distributed among ballast tanks as necessary in relation to the situation. The ship has been designed on purpose with this property to reduce the ballast water treatment implications. This implied modifications on the hull geometry (and on the capacity plan as well) to obtain a ship *resilient* to the change of loading condition, in terms of trim, list and stability. The vessel fulfills all the mandatory criteria present in the Intact Stability code (IS code) [2]; nevertheless, it has been considered worthy of a deeper investigation in terms of stability in waves.

Current ship design techniques mainly focus on the study of the block coefficient C_B , the midship section coefficient C_M and the prismatic coefficient C_P . It is common that approximated values of these form coefficients are derived from empirical formulations, e.g., the Watson-Gilfillan method [3]. Conversely to the traditional design techniques, in our work the vertical prismatic coefficient C_{VP} has been selected as the leading geometrical parameter. After the application of SGISc, vulnerabilities caused by the effect of hull-wave interaction have appeared. Therefore, the investigated hull has been systematically modified integrating the C_{VP} in the iterative design process until a satisfactory solution is reached. The proposed methodology has been obtained by a revisitation of the Lackenby's method [4], where a controlled vertical shift of the horizontal sections is done in order to reach the desired result.

The proposed methodology is intended to be used during the early design stages. Nevertheless, it is recognized that the suitable weight distribution and the proper displacement are to be supposed at this stage, as is usually the case in ship design.

The Ballast and Its Related Problem

In recent years, the introduction of alien species in a marine environment through the discharge of ballast water has been identified as a significant threat for marine biodiversity worldwide [5–7]. After a long period of development and discussion, the “*International Convention of the control and management of ship’s ballast water and sediments*” was adopted by IMO on 13 February 2004 [8]. One of the most considerable requirements is the installation on board of a ballast water treatment system. The cost of installing, operating, and maintaining such plants is not negligible; therefore, it appears evident that designing a ship with reduced need for ballast water treatment may provide economic advantages, at least during the operational life of the ship. In the literature, ship design based on the adoption of different alternatives to tackle the ballast water issue can be found [9–12]. In this paper, we decided to investigate a ship carrying a constant amount of ballast water to fix cargo handling related problems, such as excessive trim or list.

2. Second Generation Intact Stability Criteria as a Design Tool

The SGISc have been adopted as a further intact stability performance assessment tool beside the IS code. Such criteria represent an important innovation and it is expected they will improve ship performances in terms of safety of navigation for stability in waves. Currently, interim guidelines on SGISc have been finalised by the IMO [1]. Since SGISc are not fully validated on a sufficient amount of vessels, they have been issued in a non-mandatory form, launching a trial period during which feedbacks from their application will be gathered by the IMO for further improvement. Three of the most important innovations introduced by SGISc are listed below:

- SGISc consider the ship stability in a seaway condition;
- SGISc are physically based and performance-oriented;
- SGISc have been developed adopting the multi-layered approach.

In particular, the multi-layered approach consists of three assessment levels for each stability failure mode, with increasing accuracy as well as increasingly detailed knowledge about design and computational time. Since it has been recognized that not all the vulnerability problems might be efficiently fixed acting only on the ship design, Operational Measures (OM) have also been introduced in the multi-layered framework. In Figure 1 a graphical representation of this approach is given.

Figure 1. Graphical representation of the multi-layered approach.

Figure 1 shows that there is no hierarchy among levels. This means that it is possible to begin the assessment process at any level, with or without OM. Nevertheless, a logical application flow suggests starting the process from the first vulnerability level (i.e., the simplest and fastest criterion) moving up to the third level (i.e., the most complex and time consuming), named Direct Stability Assessment (DSA), passing through the second vulnerability level (Lv2). Operational measures can be divided into two typologies: Operational Guidance (OG) and Operational Limitations (OL). The first one provides specific suggestion to the master on the ship handling in specified sea states, while OL define a set of environment-related limitations on the navigation. A detailed description about the inner structure of OM, their relationship with the design assessment (i.e., Lv1, Lv2 and DSA) and some applicative examples are given in [13,14].

Five stability failure modes are addressed: parametric roll (PR), pure loss of stability (PL), stability in dead ship condition (DS), excessive acceleration (EA) and surf-riding/broaching-to (SR). Details about the physics and the main features for these phenomena are given in [15–19], while example of vulnerability level application can be widely found in the literature [20–23]. In the following paragraphs, a brief description of the criteria is given, with reference to the vulnerability levels.

2.1. First Vulnerability Levels

PR and PL stability failure modes are directly related to the variation of the transverse metacentric height due to the interaction between the hull and the wave profile. This relationship is considered in the first-level vulnerability criteria even if there are some simplifications. In particular, Lv1 of PL considers the loading condition not to be vulnerable if (1) is satisfied.

$$GM_{min} \geq R_{PLA} \quad (1)$$

where GM_{min} is the metacentric height evaluated for an even keel waterline passing through the wave trough; $R_{PLA} = 0.05$ m is the standard, i.e., the threshold to be satisfied. The considered regular wave has a length equal to the ship length and a steepness S_w equal to 0.0334.

On the contrary, a loading condition is deemed not vulnerable to the PR stability failure mode if (2) is satisfied.

$$\frac{\delta GM_1}{GM} \leq R_{PR} \quad (2)$$

where GM is the metacentric height evaluated in calm water; δGM_1 is the difference, divided by two, between the metacentric heights evaluated for even keel waterlines passing through the wave crest and trough; R_{PR} is defined as a function of length, breadth, amidship coefficient and bilge keel area. The considered wave has a length equal to the ship length and a steepness S_w equal to 0.0167. Both Lv1 for PR and PL should comply with the requirement reported in (3)

$$C_{\nabla} = \frac{\nabla_D - \nabla}{A_{WL} \cdot (D - d)} \geq 1.0 \quad (3)$$

where ∇_D is the immersed volume evaluated at a draught equal to D ; ∇ is the immersed volume at draught equal to d ; D is the ship depth; d is the draft for the considered loading condition.

The criterion for the first vulnerability level of DS has been developed directly through a minor modification of the current weather criterion defined in the IS code. In particular, the table presenting the relation between the roll period and the wave steepness has been replaced with that contained in the guidelines for alternative assessment of the weather criterion [24].

First level criterion for EA has been directly derived from the corresponding Lv2, although some simplification on environmental condition has been introduced. A ship is considered not vulnerable to Lv1 of EA if (4) is satisfied.

$$C_{EA1} = \varphi \cdot k_L \cdot (g + 4\pi^2 \cdot \frac{h_r}{T_\phi^2}) \leq R_{EA1} \quad (4)$$

where φ is the characteristic roll amplitude; k_L is a coefficient taking into account simultaneous action of roll, yaw and pitch motions; g is the gravity acceleration; T_ϕ is the roll period; h_r is the vertical distance between the roll axis and the highest point where crew or passengers may be present; $R_{EA1} = 4.64 \text{ m} \cdot \text{s}^{-2}$ is the standard.

Finally, the Lv1 of SR stability failure mode criterion is a very simple formulation where only few ship characteristics are considered. This criterion deems a ship not vulnerable to SR if rules in (5) are satisfied.

$$L \geq 200 \text{ m} \quad \text{and} \quad Fn \leq 0.30 \quad (5)$$

where L is the ship length and Fn is the Froude number evaluated at the ship service speed ($Fn = V_S / \sqrt{g \cdot L}$).

2.2. Second Vulnerability Levels

All the second level vulnerability criteria have been developed with a similar structure reproducing a long-term analysis over a selected wave scatter table. The criterion for each phenomenon is formulated as reported in (6).

$$C_{LT} = \sum_{i=1}^N C_{ST_i} \cdot W_{S_i} \quad (6)$$

where C_{ST_i} is the short-term index; W_{S_i} is the weighting factor for a specific sea state as defined by the selected wave scatter table; N is the total number of sea states defined by the wave scatter table. A vessel is considered not vulnerable if the long-term criterion C_{LT} is equal to or lower than the standard R .

According to the stability failure mode under assessment, different short-term indexes and standards should be considered. A technical description of the complete procedure to evaluate each short-term index is not provided in this paper, but it can be found thoroughly described in the literature [14,25,26] and in the IMO circular [1]. For the DS stability failure mode, the short-term index is evaluated by means of a dynamic-based simplified model depending on the wave and wind energy spectra, together with the roll motion response amplitude operator (RAO). To evaluate the short-term index for the EA stability failure mode, the analysis of lateral acceleration RAO and wave energy spectrum is required. The short-term index for the SR stability failure is obtained comparing the ship Froude number with the critical Froude number, computed by means of an iterative procedure where the balance between the hull resistance and the propeller thrust at wave celerity is realized. Finally, for both the PL and PR stability failure modes, two separate short-term indexes are required. In PL, the short-term indexes are evaluated considering the righting-lever vanishing angle and the static equilibrium angle under the action of a given heeling lever; the vessel should be considered balanced in sink and trim on a regular wave having the same length as the ship with different heights and wave crest positions. The two short-term indexes for the PR stability failure mode consider the variation of metacentric height for a set of 16 waves and the maximum roll angle evaluated by a one degree of freedom time domain mode; for the second index, simulations are required taking into account a set of different ship speeds in head and following regular waves.

3. Application Case

A ballast-free containership has been investigated and its geometry has been systematically modified in order to make it compliant with the SGISc.

The ship is compliant with the first generation intact stability criteria (i.e., those criteria reported in the IS code). For this investigation, the loading condition having the lowest metacentric height has been selected, i.e., the full load at arrival. This configuration has been selected because, in case of a limited initial stability, the interaction between the hull and the encountered waves may quickly lead to a dangerous condition in terms of ship stability. For this loading condition the tanks are considered to be filled at 10% of their capacity. The containers are assumed to be loaded uniformly distributed onboard, having a unitary weight of 11.9 t. A representation of the hull is given in Figure 2 and data about the main dimensions and the selected loading conditions are given in Table 1.

Table 1. Main dimensions of the vessel.

Main Dimensions				
Overall length	L_{OA}	234.50		m
Length at waterline	L_{WL}	220.53		m
Length between perpendicular	L_{BP}	216.43		m
Maximum breadth	B	35.00		m
Depth	D	16.60		m
Draft	d	9.85		m
Waterplane area	A_{WL}	6521		m ²
Displacement	Δ	52,414		t
Vertical position of CoG	VCG	16.50		m
Longitudinal position of CoG	LCG	97.27		m

Figure 2. Representation of hull surface and sections processed by the computational code.

Since no information about dimensions of bilge keels is available, they are assumed to have a length $l_{BK} = 70.0$ m and a span $b_{BK} = 0.35$ m. The application of SGISc has been carried out by a in-house developed code [15]. All stability failure modes have been investigated, with the only exception of SR since the ship length, longer than 200 m, justifies its overlooking. For those stability failure mode where the ship should be balanced in trim and sinkage on a wave, another in-house computational code has been used [27]. Results are shown in Tables 2 and 3.

Summary of Results

In Table 4 a summary of the results is reported. The identified vulnerabilities are relevant to PL and PR. It is worth mentioning that such stability failures are usually mentioned as possibly affecting containerships. It appears also that the Lv2 for the DS is not met; however, according to the multi-layered approach, the vessel is considered to be not vulnerable to this failure mode since the Lv1 criterion is met. This represents an inconsistency between vulnerability levels, because each Lv1 should be less demanding compared with the corresponding Lv2.

Table 2. Application of first vulnerability levels to the Full load at arrival loading condition.

Results of Level 1					
PR	$\frac{\delta GM_1}{GM}$	C_{∇}	R_{PR}	Rule	
	3.288	1.082	0.367	$\frac{\delta GM_1}{GM} \leq R_{PR}$ and $C_{\nabla} \geq 1.0$	
PL	GM_{min} (m)	C_{∇}	R_{PLA} (m)	Rule	
	−1.941	1.082	0.050	$GM_{min} \geq R_{PLA}$ and $C_{\nabla} \geq 1.0$	
DS	φ_0 (deg)	Area b / Area a	φ_{deck} (deg)	$\varphi_{0,lim}$ (deg)	Rule
	9.5	2.129	16.9	16.0	$\varphi_0 \leq \min(\varphi_{0,lim}; 0.8\varphi_{deck})$ and $b/a \geq 1.0$
EA	$C_{EA1} = \varphi \cdot k_L \cdot (g + 4\pi^2 \cdot \frac{h_r}{T_\phi^2})$ (m · s ^{−2})		R_{EA1} (m · s ^{−2})		Rule
	1.173		4.640		$C_{EA1} \leq R_{EA1}$

Table 3. Application of second vulnerability levels to the Full load at arrival loading condition.

Results of Level 2					
PR	C1	C2	R_{PR1}	R_{PR2}	Rule
	0.998	0.064	0.06	0.025	$C1 \leq R_{PR1}$ and $C2 \leq R_{PR2}$
PL	CR1	CR2	R_{PL0}		Rule
	0.999	0.720	0.06		$\max(CR1; CR2) \leq R_{PL0}$
DS	C_{DS}		R_{DS}		Rule
	0.137		0.06		$C_{DS} \leq R_{DS}$
EA	C_{EA2}		R_{EA2}		Rule
	0.00		3.9×10^{-4}		$C_{EA2} \leq R_{EA2}$

Table 4. Summary of application results for vulnerability levels.

Loading Condition—Full Load at Arrival			
Stability failure	Level 1	Level 2	Total Criterion
DS	MET	NOT MET	MET
EA	MET	MET	MET
PR	NOT MET	NOT MET	NOT MET
PL	NOT MET	NOT MET	NOT MET

4. Hull Geometry Systematic Modification

The ship has been found to be vulnerable at PL and PR stability failure modes. Therefore, a further insight is carried out on this issue, considering the full load arrival condition. In this paragraph, a procedure to modify the hull geometry in a systematic way is defined in order to fix the ship vulnerability revealed in the previous analysis. Besides, as already mentioned, also the bilge keels dimensions have been taken into account as a possible way to solve the vulnerabilities. Due to the physics at the basis of the considered phenomena, the PL compliance will not be affected by a changing of bilge keels. On the other side, as a first attempt, a resolution of PR vulnerability has been pursued modifying only the dimensions of the bilge keels. The bilge keels have been enlarged to reach a length of about 39% L_{BP} . Keeping their length fixed, it is pointed out that the minimum required span of bilge keel that is able to solve the PR vulnerability is 1.10 m. This value has been considered really significant and not practicable; therefore, the issue of PR vulnerability has been postponed after the resolution of PL vulnerability by means of hull geometry change. It has been assumed that the possible improvement in terms of PL vulnerability could also imply a positive effect on PR. It is reasonable to expect this because the two stability failures are physically related with the righting arm variation in waves. To solve the PL vulnerability, the change of the vertical prismatic coefficient C_{VP} of the ship has

been identified as a possible effective strategy. This is also suggested in [28] where it is shown how C_{VP} and PL are related.

4.1. Definition of a Systematic Methodology to Modify C_{VP}

The process identified to change C_{VP} has been inspired by the so called Lackenby's procedure that is used to modify the longitudinal prismatic coefficient C_P with a shifting of the transverse sections in the longitudinal direction. In Lackenby's original procedure, reference is made to a dimensionless diagram of transverse submerged areas. In the proposed procedure, in order to act on the C_{VP} , reference is made to a dimensionless diagram of waterplane areas. The diagram describes the ratio between waterplane area A_{WL} and maximum waterplane area $A_{WL,max}$ as a function of the ratio between the vertical coordinate z and maximum draft d_{max} . In Figure 3, a general example of such diagram is given. On the horizontal axis the ratio between the vertical coordinate and the maximum draft is given, while the vertical axis shows the ratio of the waterplane area to the maximum waterplane area.

Figure 3. Dimensionless diagram of waterplane area of vessel.

It can be easily demonstrated that, the area underlying the dimensionless diagram represents the C_{VP} . In (7), this demonstration is given.

$$A_{\text{diagram}} = \int_0^1 \frac{A_{WL}}{A_{WL,max}} \cdot d\left(\frac{z}{d_{max}}\right) \quad (7a)$$

$$= \frac{1}{A_{WL,max} \cdot d_{max}} \cdot \int_0^1 A_{WL} \cdot dz \quad (7b)$$

$$= \frac{\nabla}{A_{WL,max} \cdot d_{max}} = C_{VP} \quad (7c)$$

It is evident that, with the aim to increase C_{VP} , the increment of such area is to be pursued. Each point of the diagram corresponds to a specific waterplane, characterized by a specific value of A_{WL} . In order to increase C_{VP} by the waterplanes, without modifying their geometry, the points must be shifted horizontally in the graph. This implies that only the vertical position of waterlines will be modified. Moving all the points of the curve, except the two extreme ones, a change of the entire hull geometry is possible, keeping unchanged the topside. Looking at the diagram in Figure 3, it is obvious that the various points must be shifted toward the left to obtain an increase in C_{VP} . After the definition of the new position of the points on the diagram, it is necessary to lead back the vertical coordinates of each waterplane to a dimensional value. Since d_{max} varies after the transformation, the

new maximum draft can be calculated from the value of C_{VP} , causing the hull volume to be the same, as indicated in (8).

$$\nabla = \nabla' \Rightarrow A_{WL,max} \cdot d_{max} \cdot C_{VP} = A_{WL,max} \cdot d'_{max} \cdot C'_{VP} \Rightarrow d'_{max} = \frac{C_{VP}}{C'_{VP}} \cdot d_{max} \quad (8)$$

The quantities ∇' , d'_{max} and C'_{VP} are respectively the submerged volume, the maximum draft and the vertical prismatic coefficient referring to the modified hull.

The whole methodology described above, can be easily implemented in a semi-automatic procedure involving the use of a CAD software and a computational script in Matlab®. The process is initialized describing the hull geometry by horizontal sections. The computational code, guided by identified constraints, is able to modify the geometry according to the desired C_{VP} : as constraints it has been decided to keep constant the distance between the waterlines in the neighbourhood of the design water line (DWL) and of the base line, which represent the extreme of the domain. The vertical shift of intermediate waterlines is ruled by a linear relationship relying on the initial distance from the DWL and the base line. The larger the distance from the domain extremes, the greater the vertical shift of a waterline.

4.2. Implementation of the Procedure

In Figure 4, the comparison between the original curve and a modified curve by means of the described methodology is shown.

Figure 4. Comparison between original and modified curve evaluated for generic increment of C_{VP} .

During the geometry change, other parameters significant for the stability assessment are evaluated, e.g., the area of the amidship transversal section. The new draft, ensuring the same submerged volume, is calculated by linear interpolation knowing the correspondent displacement. According to the value of the new draft, the new depth is calculated in (9).

$$D' = D - d_{max} + d'_{max} \quad (9)$$

Finally, it is assumed that the ratio between the vertical position of the center of gravity VCG over the depth D is kept constant. Therefore, the new VCG' is calculated as shown in (10).

$$\frac{VCG}{D} = \frac{VCG'}{D'} \Rightarrow VCG' = \frac{D'}{D} \cdot VCG \quad (10)$$

Obviously, this assumption is an approximation, deemed valid in this preliminary phase of the project.

4.3. Application of the Procedure to the Container Vessel

The procedure described above has been undertaken and after every increase in the C_{VP} , the PL criteria for both the Level 1 and Level 2 have been applied seeking to fix the vulnerability to this stability failure mode. Starting from the $C_{VP} = 0.788$, referring to the Full load condition at arrival, it has been increased with a variable increment. In Figure 5, samples of the dimensionless diagrams of waterplane areas are reported for a set of modified C_{VP} . The red line with circle represents the original curve, while the other lines, depicted in a grayscale, represent the curves of the modified hulls. The intermediate results are reported in Table 5. It is evident that the increment of C_{VP} allows some improvements of the results, but it is not possible to overcome the vulnerability to PL. It has been decided to suspend the hull modifications at a $C_{VP} = 0.867$, since an extreme value of the coefficient has been reached for the investigated ship typology. Although the non-vulnerability to the PL stability failure mode has not been reached only acting on the vertical prismatic coefficient, it has been deemed feasible to fix the vulnerability through a limited change of the VCG assumed. This allows us to keep a reasonable hull form with a C_{VP} lower than 0.860.

Table 5. Application of vulnerability levels for pure loss of stability to the Full load at arrival loading condition.

Pure Loss of Stability—Lv 1				
C_{VP}	GM_0 (m)	R_{PLA} (m)	C_{∇}	Result
0.788	−1.941	0.05	1.082	NOT MET
0.845	−0.522	0.05	1.074	NOT MET
0.852	−0.521	0.05	1.074	NOT MET
0.854	−0.280	0.05	1.073	NOT MET
0.857	−0.226	0.05	1.073	NOT MET
0.863	−0.044	0.05	1.073	NOT MET
0.867	−0.038	0.05	1.073	NOT MET
Pure Loss of Stability—Lv 2				
C_{VP}	CR_1	CR_2	R_{PL0}	Result
0.788	0.999	0.720	0.06	NOT MET
0.845	0.155	0.080	0.06	NOT MET
0.852	0.092	0.080	0.06	NOT MET
0.854	0.090	0.080	0.06	NOT MET
0.857	0.080	0.065	0.06	NOT MET
0.863	0.065	0.065	0.06	NOT MET
0.867	0.064	0.016	0.06	NOT MET

Outcomes shown in Table 6 point out that lowering the VCG of about 2% is sufficient to make not vulnerable to the PL failure mode, the hull geometry having a $C_{VP} = 0.857$. For this reason, this approach has been evaluated as effective and this hull has been selected as a good base for further investigations. This choice is also supported by the fact that this value is a balanced trade-off between the positive results and the hull geometry modification. Furthermore, the reduction of VCG required is sufficiently small and it has not significantly compromised the realistic application case.

Figure 5. Variation of the dimensionless diagram of waterplane area as function of C_{VP} .

Table 6. Application results for pure loss of stability to Full load at arrival loading condition considering $C_{VP} = 0.857$ and VCG reduction of about 2%.

Pure Loss of Stability—Lv 1				
C_{VP}	GM_0 (m)	R_{PLA} (m)	C_{∇}	Result
0.857	0.087	0.05	1.082	MET
Pure Loss of Stability—Lv 2				
C_{VP}	CR_1	CR_2	R_{PL0}	Result
0.857	0.037	0.012	0.06	MET

5. Ship Assessment after Modification

The modifications undertaken above define a new vessel, fully compliant with both the first and the second generation intact stability criteria. The hull geometry changes implied a reduction of the moulded depth from an initial value of 16.60 m to 15.77 m, while the maximum breadth is kept constant. As a consequence of this reduction, the height of the holds has been reduced. However, it has been considered as fundamental not to compromise the number of containers that can be stored onboard. Therefore, it has been decided to modify the topside. After this further modification, the final hull depth is equal to 16.05 m. Because of the geometrical hull modifications carried out, the equivalent number of containers stored in the holds can be reached with a hull depth lower than the original one. In Figure 6, three dimensional views of the new vessel are shown, inclusive of the internal subdivisions and stored containers.

(a) View of the main deck

(b) View of the holds

Figure 6. 3D views of the modified containership.

After this step, the new ship is able to carry the same number of containers of the model ship, i.e., 2878 TEU. The lightship weight together with the relevant center of gravity (CoG) coordinates have been evaluated and compared with the lightship weight of the original ship (Table 7). It has been decided to keep fixed the longitudinal position of the CoG. On the contrary, the VCG of each lightship item has been evaluated with the following assumptions: the VCG of the propulsion item has been left unchanged; the distance between the CoG of the superstructure item and the main deck has been kept fixed; the VCG of the hull and the outfitting items has been evaluated according to the assumption described in (10). As a result, the changes of the weight and the longitudinal coordinate can be deemed negligible, while the change of VCG is a bit more significant.

Table 7. Main items of the lightship weight before and after the modification.

Item	Original Vessel			Modified Vessel		
	W (t)	LCG (m)	VCG (m)	W (t)	LCG (m)	VCG (m)
Hull	11,989	106.37	9.20	12,062	106.37	8.90
Superstructure	974	49.50	23.90	974	49.50	23.35
Propulsion	1754	43.08	10.58	1754	43.08	10.58
Outfittings	2631	74.74	18.65	2631	74.74	18.03
Lightship weight	17,348	91.98	11.60	17,421	92.04	11.25

In order to update the loading conditions after the modifications, as a first step the amount of ballast to keep onboard has been estimated assuming that it could be sufficient both to overcome the vulnerability for the PL failure mode and to balance a maximum potential trim of about 0.80% of L_{BP} . As a result, the amount of ballast stored onboard is 2400 t. This amount ensures the possibility to handle heel angles up to 22 deg and longitudinal shift of the CoG of cargo up to 8.0 m. The loading conditions of the new vessel have been redefined as reported in Table 8, with the maximum number of containers on board (2787 TEU).

Table 8. Loading conditions of modified vessel.

Loading Conditions			
	Full Load at	Departure	Arrival
Δ	(t)	56,834	52,350
d	(m)	9.66	9.03
VCG	(m)	14.44	15.44
GMT	(m)	1.77	1.13
LCB	(m)	95.72	96.68
LCG	(m)	95.73	96.66
Trim (+ by stern)	(m)	0.23	−0.23

Finally, the SGISc have been applied to the modified ship for both loading conditions and the obtained results are reported in Tables 9–12. As expected, the vulnerability to the PL failure mode has been solved. Moreover, this procedure has also brought benefits for PR; indeed, the ship is now not vulnerable to this stability failure mode although the dimensions of the bilge keel have been left unchanged from the original size. For sake of completeness, beside final SGISc application, an assessment of the first generation criteria has been successfully carried out for both the loading conditions.

Table 9. Application of first vulnerability levels to Full load at departure loading condition after the modification.

Full Load at Departure—Lv 1					
PR	$\frac{\delta GM_1}{GM}$ 0.344	C_{∇} 1.062	R_{PR} 0.367	$\frac{\delta GM_1}{GM}$ and $C_{\nabla} \geq 1.0$	
PL	GM_{min} (m) 0.674	C_{∇} 1.062	R_{PLA} (m) 0.05	$GM_{min} \geq R_{PLA}$ and $C_{\nabla} \geq 1.0$	
DS	φ_0 (deg) 2.126	Area b / Area a 4.157	φ_{deck} (deg) 16.02	$\varphi_{0,lim}$ (deg) 16.00	$\varphi_0 \leq \min(\varphi_{0,lim}; 0.8\varphi_{deck})$ and $b/a \geq 1.0$
EA	$C_{EA1} = \varphi \cdot k_L \cdot (g + 4\pi^2 \cdot \frac{h_r}{T_{\phi}^2})$ (m · s ⁻²) 2.140		R_{EA1} (m · s ⁻²) 4.640		$C_{EA1} \leq R_{EA1}$

Table 10. Application of second vulnerability levels to Full load at departure loading condition after the modification.

Full Load at Departure—Lv 2					
PR	C1 0.062	C2 8.52×10^{-5}	R_{PR1} 0.06	R_{PR2} 0.025	<i>Rule</i> $C1 \leq R_{PR1}$ and $C2 \leq R_{PR2}$
PL	CR1 0.007	CR2 0.001	R_{PL0} 0.06		<i>Rule</i> $\max(CR_1; CR_2) \leq R_{PL0}$
DS	C_{DS} 2.35×10^{-5}		R_{DS} 0.06		<i>Rule</i> $C_{DS} \leq R_{DS}$
EA	C_{EA2} 0.00		R_{EA2} 3.90×10^{-4}		<i>Rule</i> $C_{EA2} \leq R_{EA2}$

Table 11. Application of first vulnerability levels to Full load at arrival loading condition after the modification.

Full Load at Arrival—Lv 1					
PR	$\frac{\delta GM_1}{GM}$ 0.567	C_{∇} 1.069	R_{PR} 0.367	$\frac{\delta GM_1}{GM}$ and $C_{\nabla} \geq 1.0$ <i>Rule</i>	
PL	GM_{min} (m) −0.060	C_{∇} 1.069	R_{PLA} (m) 0.05	$GM_{min} \geq R_{PLA}$ and $C_{\nabla} \geq 1.0$ <i>Rule</i>	
DS	φ_0 (deg) 3.656	$Area\ b / Area\ a$ 5.346	φ_{deck} (deg) 17.5	$\varphi_{0,lim}$ (deg) 16.0	$\varphi_0 \leq \min(\varphi_{0,lim}; 0.8\varphi_{deck})$ and $b/a \geq 1.0$ <i>Rule</i>
EA	$C_{EA1} = \varphi \cdot k_L \cdot (g + 4\pi^2 \cdot \frac{h_r}{T_\phi^2})$ (m · s ^{−2}) 1.517		R_{EA1} (m · s ^{−2}) 4.640		$C_{EA1} \leq R_{EA1}$ <i>Rule</i>

In Table 13, a summary of vulnerabilities for the full load at arrival loading condition of the modified ship is shown. The full load at departure loading condition has been found to be compliant with all the vulnerability levels at the same time. Therefore, after a limited variation of the VCG, the procedure to increase C_{VP} has been enough to solve the initial vulnerabilities; although an appropriate quantity of ballast kept on board is required.

Table 12. Application of second vulnerability levels to full load at arrival loading condition after the modification.

Full Load at Arrival—Lv 2					
PR	C1 0.436	C2 2.64×10^{-4}	R_{PR1} 0.06	R_{PR2} 0.025	Rule $C1 \leq R_{PR1}$ and $C2 \leq R_{PR2}$
PL	CR1 0.029	CR2 0.012	Rule $\max(CR1; CR2) \leq R_{PL0}$		
DS	C_{DS} 2.50×10^{-5}		R_{DS} 0.06	Rule $C_{DS} \leq R_{DS}$	
EA	C_{EA2} 0.00		R_{EA2} 3.90×10^{-4}	Rule $C_{EA2} \leq R_{EA2}$	

Table 13. Summary of application results of vulnerability levels for Full load at arrival loading conditions.

Loading Condition—Full Load at Arrival			
Stability failure	Level 1	Level 2	Total Criterion
DS	MET	MET	MET
EA	MET	MET	MET
PR	NOT MET	MET	MET
PL	NOT MET	MET	MET

5.1. KG Limiting Curves Comparison

As a further analysis, the maximum and minimum KG limiting curves have been evaluated for the original and modified hulls. In Figure 7, the outcomes of the analysis are shown. On the horizontal axis we report the drafts, while the vertical axis represents the KG values. For each stability failure mode is given the corresponding maximum limiting curve, except for the EA which is represented by a minimum limiting curve. The maximum KG curve of each stability failure mode is obtained taking the maximum KG between the corresponding Lv1 and Lv2. The total maximum KG curve (black line) is obtained considering the minimum KG value among the limiting curve of PR, PL and DS.

Figure 7. KG limiting curves of the original and modified hulls.

The grey area highlights the KG domain for a loading condition. Considering a single draft, the KG value within the domain complies with all the assessed stability failure modes at the same time. It is possible to assume that the domain area is a parameter to qualitatively identify the improvement due to the systematic transformation undertaken. In Figure 8 we show a comparison between the KG domain area for the original and the

modified hull. The domain area common to the two hulls is colored in grey. The green area shows the increment of domain area for the modified hull.

Figure 8. Comparison between the KG domain area of the original and modified hulls.

5.2. Lines Plan Comparison

Outcomes show that a relevant change of C_{VP} is needed to fix the identified vulnerabilities. This modification implied a significative shift of the hull waterlines. In order to evaluate the impact of this changes, the comparison of lines plans of the original and the modified vessels is given in Figure 9.

Figure 9. Comparison of lines plan for the original vessel and the modified vessel.

From the comparison, it appears that the modifications carried out on the hull geometry lead to a significant change of the fore bulb in terms of shape and dimensions. This is due to a lack of constraints on the shape of local geometries, such as those included for the domain extremes.

6. Conclusions

In this paper, the geometry of a containership has been modified in order to comply with the SGISc. The subject of this paper is a ballast-free containership, which means that a limited amount of ballast is always present on board and there is no need to load or unload ballast water to balance trim and heel after a loading condition change. The SGISc introduces some innovation in the field of intact stability analysis, e.g., the multi-layered approach and the performance-oriented assessment. In particular, the investigated typology of vessel is recognized to be possibly vulnerable to one of the phenomena addressed by the SGISc, i.e., restoring arm variation in waves. The application of the criteria pointed out that the ship is vulnerable to pure loss of stability and parametric roll. Moreover, the outcomes show that an inconsistency between Lv1 and Lv2 occurs for the DS stability failure.

In order to fix the vulnerabilities, it has been decided to modify the hull acting on the vertical prismatic coefficient as leading parameter of the transformation. Through a revised Lackenby procedure, the hull has been systematically modified and, subsequently, the PL criteria applied. By an iterative process, the hull has been modified, lowering the vulnerability level. It appeared that the single modification of the hull was sufficient to overcome the vulnerability; thus, it is necessary to make a small reduction of the vertical position of the center of gravity. The modifications, which aimed to solve the vulnerability to PL, were also effective for the PR failure mode. Once the PL and the PR failure modes have been fixed, minor adjustments to the topside and cargo distribution have been made. Finally, the modified vessel has been assessed with the SGISc, resulting in compliance with all the criteria.

In order to better analyse the effects of modifications on the hull, the maximum and minimum KG limiting curves have been evaluated and compared in terms of KG domain area. Outcomes show how the domain for the modified hull is larger than the domain of the original one. The comparison of the lines plan points out that the shape of the fore and stern bulb have been significantly affected by the proposed methodology. These changes have a relevant impact on the ship design, e.g., the hull resistance prediction or the ship seakeeping analysis may be significantly influenced.

This application points out that the SGISc may have an impact that requires a revision of the design of a vessel. Nevertheless, this application proves that it is possible to solve these issues by systematic modification of the hull geometry combined with minor adjustment on the center of gravity position.

It is worth mentioning that it is necessary to validate the proposed methodology on a larger sample of vessels not limited to ballast-free containership. In addition, other important topics of the ship design (e.g., seakeeping, maneuverability, hull resistance) are significantly affected by the hull shape modification carried out in this work. Although the stability in waves has been the main aspect addressed, it will be interesting to continue this analysis to study the impact of the proposed methodology on the other topics of naval architecture. Finally, the outcomes pointed out that constraints in the methodology are to be improved in order to avoid substantial modifications on the local hull geometry, i.e., fore bulb shape.

Author Contributions: Conceptualization, D.P., C.P.B., P.G. and N.P.; Software, N.P. and D.P.; Supervision, P.G. and C.P.B.; Writing—original draft, N.P. and D.P.; Writing—review & editing, P.G. and N.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest during preparation and publishing of this work.

Abbreviations

The following abbreviations are used in this manuscript:

CoB	Center of Buoyancy;
CoG	Center of Gravity;
DS	Dead Ship condition;
DSA	Direct Stability Assessment;
DWL	Design Waterline;
EA	Excessive Acceleration;
IMO	International Organization Maritime;
IS	Intact Stability;
Lv1	First vulnerability level;
Lv2	Second vulnerability level;
OG	Operational Guidance;
OL	Operational Limitations;
OM	Operational Measures;
PL	Pure Loss of Stability;
PR	Parametric Rolling;
RAO	Response Amplitude Operator;
SGISc	Second Generation Intact Stability criteria;
SR	Surf-Riding;
TEU	Twenty Equivalent Unit.

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