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Cost, Energy Efficiency and Carbon Footprint Analysis of Hybrid Light-Weight Bulk Carrier

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Abstract: Integrating innovative solutions for ship design has always been a great challenge for the maritime sector due to complex design and construction processes. With this scenario in mind, the objective of this study was to develop a procedure to evaluate the potential benefits arising from the integration of innovative light-weight structures in ship hull structural design. To achieve such an objective, a hybrid light-weight ship hull structural design solution, in which aluminium honeycomb sandwich panels were used to build the conventional steel inner side shell of the cargo holds, was adopted for a bulk carrier. The authors of this study used a multiple criteria decision-making approach. An optimal ship hull structural design solution was identified based on capital cost, voyage cost, annual cost, energy efficiency design index, dismantling–reselling cost, cargo transportation, energy consumption and carbon footprint. The optimal solution, identified with the multiple criteria decision-making approach, improved the ship's efficiency and costs by combining the hybrid structural design with efficient cargo transportation. In addition, using recycled aluminium was found to be a promising strategy to reduce the energy consumption and carbon footprint related to the shipbuilding process.

Keywords: hybrid structures; ship design; light-weight structures; multiple criteria decision making; aluminium honeycomb

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1. Introduction

Ship design is a complex process whose principles are constantly evolving to comply with technical innovations and regulations. A combination of multidisciplinary competencies is involved during the design phase to achieve an output able to meet different requirements and objectives (e.g., cost limitations, conformity to safety rules, and carbon emission restrictions). Therefore, a successful design process cannot avoid integrating multiple criteria in decision making. Many studies concerning advanced optimisation and decision-making approaches for ship design testify to the importance of these tasks.

Papanikolaou [1] suggested that the holistic perspective to ship design optimisation is a preferable design framework. However, its good extension to common practice still requires significant efforts in developing, integrating, and identifying relevant objectives, algorithms, and software. Similarly, an optimisation procedure based on Multiple Objectives Genetic Algorithms [1], combined with gradient-based search and utility function techniques, was developed and applied to two examples, one of which required the limitation of the environmental impact of a high-speed vessel as a result of wash wave minimisation.

The weight minimisation of the midships section of a bulk carrier was performed in [2] by applying a new optimisation approach that integrates machine-learning into general optimisation methods to reduce analysis time and improve searching ability. Turan et al. [2] focused their attention on the effects of ship structural weight optimisation—achieved via optimal steel structural elements design—on the life-cycle cost/earning of production and maintenance/repair by developing an approach to support the early design phases.

The unavoidable uncertainties involved in the design process were taken into account by Priftis et al. [3] in their multi-objective ship design methodology, which was applied to a Ro-Pax vessel case study involving the optimisation of building cost in terms of steel weight minimisation.

Advanced optimisation methods for ship design are continuously developed and applied to the whole ship design process. Among the issues attracting the marine industry's attention, ship life-cycle costs and environmental impact deserve particular attention.

Regarding the first topic, it is well-established that every industry aims to maximise their results while minimising their economic investments. The environmental implications of maritime transport are becoming of primary concern since the field accounts for more than 3% of worldwide CO_2 emissions [4] and the whole shipbuilding and ship-repairing industry is recognised to be responsible for hazardous and polluting emissions [5] during all its phases, from material retrieval to decommissioning.

The direct environmental benefit of a light-weight structure is related to the potential fuel savings, required power reduction and subsequent emission decrease. The marine industry has often addressed weight-saving purposes by adopting sandwich structures [6–8]; these solutions can combine different materials (all-metal, composite or hybrid) and can have several core configurations, ranging from corrugated [9] to lattice [10], from foam [11] to honeycomb [12], or more even complicated geometries inspired by nature [13]. The main categories currently using sandwich structures are those of pleasure boats, yachts and small navy ships, for which researchers pioneered sandwich introduction in shipbuilding [14].

The treatment of thermoset matrixes, most used in marine sandwich structures, involves complex and expensive economic processes [15], and thermoplastic matrixes are not easily manageable. In addition, separating the different constituents of a composite sandwich structure to reuse or recycle them is hardly feasible. The most common solution is to cut panels into small pieces, with further complications deriving from tough and abrasive fibres. The ineffective or impossible reuse and recycling of structures and materials can jeopardise the potential environmental benefits achievable via light-weight design. Other materials, such as aluminium or bio-based composites, could represent an alternative to traditional marine sandwich structures due to their potentially higher recyclability degree [16] even though their suitability for structural parts needs to be verified.

Issues concerning reuse, recycling, and, more generally, the environmental impact of marine structures and materials can no longer ignored or delayed [5,17]; as stated in the Hong Kong International Convention in 2009 [15], overseen by the International Maritime Organization (IMO), safe and reliable ship recycling needs to be achieved and supported by proper design, construction, operation, and recycling planning. The design phase has to account for the implications of materials and structure manufacturing, disposal, and reuse on environmental emissions. Despite developing valuable tools, such as LCA [16], to assess the environmental impact of a whole life-cycle, a proper impact-mitigation strategy would require integrating sustainability constraints and objectives with other design requirements.

A study about the most common light-weight materials and structures for marine structural application and their environmental impacts was performed in [8]. The effect of structural enhancement in reducing the light weight and level of sustainability was evaluated, and some "greener" light-weight marine structural design solutions were analysed and discussed.

Accounting for the risk involved in the ship operation, a risk-based conceptual ship design framework for bulk carriers was developed in [18] while considering the ship propulsion system, life-cycle assessment, and energy efficiency and including the conceptual ship design as part of the risk-based ship design approach. The conceptual design was based on long-term experience and statistics related to the main dimensions and hull form, resistance and propulsion, weights, initial stability, free-board, seakeeping and manoeuvrability, capital, operational, and decommissioning expenditure. An optimal design solution was identified based on the energy efficiency design index, shipbuilding, operation, and resale costs at the end of the service life. These were used as input variables in a risk-based analysis where several possible solutions for increased efficiency were also discussed, including hull line optimisation and speed reduction between others.

Considering the described scenario, the broader use of eco-friendly materials and light-weight structural solutions should be explored to match the requirement of a sustainable and light-weight design. To fully achieve this objective, a ship design procedure capable of assessing the design solution in terms of technical and functional requirements, energy efficiency, carbon footprint, and costs is required.

The main objective of this study, which is aligned with the mentioned issues, was to evaluate the potential benefits arising from the integration of innovative light-weight structures in ship design. In the present work, a hybrid light-weight ship structural design solution, where aluminium honeycomb sandwich panels were used to replace the steel plates of the inner side shell, was adopted for a bulk carrier, thus creating a hybrid structure and supporting longitudinal stiffer reinforcements [19].

The design solution assessment was carried out with a multiple criteria decision-making approach. This approach involved several aspects of the ship's life-cycle, from production to operation and decommissioning. The proposed design solution demonstrated a high potential to enhance the ship's reliability, cost, and efficiency. Light-weight structures are promising alternatives to conventional structural design solutions and materials; moreover, they may pave the way for more sustainable shipbuilding and eco-friendly structural solutions.

The current study extends previous work on light-weight ship hull structural design. Considerations concerning the ship decommissioning expenditure, energy consumption and carbon footprint related to ship manufacturing are introduced. In particular, the energy consumption and the environmental impact deriving from material production and structure dismantling were estimated to include environment-related considerations in the ship design process. The effect on the costs deriving from scrap reselling was also considered. An optimal design solution was identified, via the multiple criteria decision-making approach, based on the capital, voyage cost, annual cost, energy efficiency design index, dismantling–reselling cost, cargo transportation, energy consumption and carbon footprint of the ship hull structure. More in detail, the multiple criteria decision-making Technique of Order Preference by Similarity to Ideal Solution (TOPSIS) was employed and two artificial alternatives were compared: the first one mainly focused on parameters related to costs, and the second one mainly concerned the energy consumption and carbon footprint of the production of the material and dismantling processes.

2. Environmental Implications of Hybrid Light-Weight Design in Shipbuilding

The multi-objective design procedure developed for the hybrid ship, considered as a case study, was enriched with considerations related to the manufacturing and the decommissioning phases. This section presents the data collected to evaluate the impact of the proposed solution in terms of energy consumption and carbon footprint.

To achieve the mentioned objective, information was collected from the scientific literature concerning two crucial stages of materials' life-cycle: manufacturing and decommissioning/recycling. In particular, data on energy requirements and carbon footprint for primary and secondary (recycling) production processes were retrieved from the Report on the Environmental Benefits of Recycling [20,21] of the Bureau of International Recycling. Single-stream processes consider the recovery of a fully refined product for final use. The materials involved in the analysis were aluminium and steel, according to the considerations provided in Sections 3 and 4. A summary of the reference study's main findings is reported in Table 1. The data represent average values of energy requirements and carbon footprint of the raw material production processes.

Table 1. Primary and secondary processes' average specifications for raw material production.

Material	Primary Production			Secondary Production		
	Manufacturing Process	Energy Consumption, E_p (MJ/kg)	Carbon Footprint, C_p (tonnesCO_2)	Manufacturing Process	Energy Consumption, E_s (MJ/kg)	Carbon Footprint, C_s (tonnesCO_2)
Steel	BF-BOF DRI + EAF	21.9 26.7	1.97 1.76	EAF	11.7	0.7
Aluminium	Bayer Hall Héroult	184.4	13.3	Remelting and casting	5	0.6

The ship dismantling process is also an important economic sector that severely impacts human health and the environment. Recently, a promising process of change in environmental safeguard and safety and human life protection has been taking place. A key element of this change seems to be the improvements brought by complementing existing national, but mainly international (IMO), and European Community (EU) regulatory rules [22]. Parts of such regulations are intended to prevent, reduce, minimise and eliminate accidents, injuries and other adverse effects on human health and the environment caused by ship recycling.

It is worth mentioning that the recycling process implies economic revenues, which are one order of magnitude higher for aluminium scrap than for steel. The potential gains may be calculated considering an average of 3760 €/tonne for aluminium (R_A) and an average of 376 €/tonne for steel (R_S) [23].

3. Alternative Hybrid Light-Weight Ship Hull Structural Design

The methodology used in Ref. [19] was employed here. A hybrid light-weight ship bulk carrier structural design was constructed based on the integration of aluminium honeycomb sandwich structures as a replacement for the conventional steel inner side shell of the cargo hold of a bulk carrier. The structural design involved minimising costs, using light-weight materials, and maximising annual cargo and ultimate strength. The ship's total cost evaluation was based on the annual operating cost, OPEX, which is the sum of the salary of crew members and costs related to the stores and supplies, insurance, port expenses, and annual fuel. The capital cost, CAPEX, accounts for all costs of building a vessel associated with material, labour, overheads, and profit. Its evaluation was based on governing parameters such as ship size, weight, and propulsion power. The decommissioning cost, DC, was evaluated according to general formulations, reported in the following section, accounting for ship dismantling as a light-weight function.

The optimisation procedure applied to identify the optimal design solution involved decision variables, constraints and objective functions.

3.1. Decision Variables

The decision variables involved in the optimisation process include the ship hull plate thickness, $t_{i,c}$ with a step of 0.5 mm, defined as:

$$t_{min} \leq t_{i,c} \leq t_{max} \quad (1)$$

the material yield stress, σ_y, as a discrete variable, according to the existing shipbuilding-steels:

$$\sigma_{y,\ min} \leq \sigma_{y,\ upper\ shell} \leq \sigma_{y,\ max} \quad (2)$$

$$\sigma_{y,\ min} \leq \sigma_{y,\ lower\ shell} \leq \sigma_{y,\ max} \quad (3)$$

$$\sigma_{y,\ min} \leq \sigma_{y,\ intermediate\ shell} \leq \sigma_{y,\ max} \quad (4)$$

the span, l, which is a discrete variable, with a step of the stiffener spacing, s_i:

$$2s_i \leq l \leq 5s_i \quad (5)$$

3.2. Constraints for Steel Parts

The constraints applied to steel structures were derived from DNV rules [24] and are as follows:

(a) Minimum plate thickness (local strength):

$$C_1 : t_{i,c} - t_{i,min} \geq 0 \tag{6}$$

where:

$$t_{i,min} = \max\left(\frac{15.8k_a s_i \sqrt{p_i}}{\sqrt{\sigma_i}} + t_k, c_i + \frac{0.05L}{\sqrt{f_i}} + t_k\right) \tag{7}$$

$t_{i,c}$ is the current plate thickness, k_a is a coefficient that depends on the span to stiffener spacing ratio, p_i is the design pressure load, σ_i is the allowable stresses, t_k is the corrosion addition, c_i is the base minimum thickness, and f_i is the material factor, a discrete value that depends on the yield stress of the material and varies from 1.00 for a yield stress of 235 MPa to 1.43 for a yield stress of 390 MPa;

(b) the minimum section modulus (longitudinal strength) is defined as:

$$C_2 : Z^{deck} - Z^{deck}_{min} \geq 0 \tag{8}$$

where:

$$Z^{deck}_{min} = \max\left(\frac{C_W L^2 B(C_B + 0.7)}{f_1}, \frac{|M_S + M_W|}{175f_1}\right), \tag{9}$$

Z^{deck} is the current midship section modulus at the deck, and

$$C_3 : Z^{bottom} - Z^{bottom}_{min} \geq 0 \tag{10}$$

where:

$$Z^{bottom}_{min} = \max\left(\frac{C_W L^2 B(C_B + 0.7)}{f_1}, \frac{|M_S + M_W|}{175f_1}\right) \tag{11}$$

and Z^{bottom} is the current midship section modulus at the bottom.

(c) the minimum critical buckling stress, defined as:

$$C_4 : \eta_i \sigma_{c,i} - \sigma_{a,i} \geq 0 \tag{12}$$

where η_i is the usage factor and

$$\sigma_{a,i} = \frac{M_S + M_W}{I_N}(z_n - z_{a,i}) \tag{13}$$

where M_S is the still water and M_W is the wave-induced bending moments, as given by the rules, and I_N is the moment of inertia of the hull girder. The critical buckling stress, $\sigma_{c,i}$, is defined as:

$$\sigma_{c,i} = \begin{cases} \sigma_{el,i} \text{when} \sigma_{el,i} \leq \sigma_{y,i}/2 \\ \sigma_{y,i}\left(1 - \frac{\sigma_{y,i}\sigma_{el,i}}{4}\right) \text{when } \sigma_{el,i} > \sigma_{y,i}/2 \end{cases} \tag{14}$$

where:

$$\sigma_{el,i} = 0.9kE\left(\frac{t_{i,c} - t_k}{1000s_i}\right)^2 \tag{15}$$

is the ideal compressive buckling stress for plates in uniaxial compression and

$$\sigma_{el,i} = 3.8E\left(\frac{t_{w,i,c} - t_k}{h_{w,i}}\right)^2 \quad (16)$$

is the ideal compressive buckling stress for stiffeners in uniaxial compression, where $h_{w,i}$ is the web height and $t_{w,i,c}$ is the web thickness and

$$\sigma_{el,i} = 0.001\,E\frac{I_A}{A\,l^2} \quad (17)$$

is the ideal compressive stress for the stiffeners in lateral buckling mode, I_A is the moment of inertia about the axis perpendicular to the expected direction of buckling, A is the cross-sectional area, and l is the span of the stiffener.

3.3. Constraints for AHS Parts

The constraints for the aluminium honeycomb sandwich structural parts were derived from Hexcel design guidelines [25] and include:

(a) The deflection is defined as:

$$C_5 : \delta_f - \frac{2k_1 q b^4 \lambda}{E_f t_f h^2} \geq 0 \quad (18)$$

where k_1 is the panel parameter used for simply supported plate, q is the uniformly distributed load, b is the plate width, λ is the bending correction factor for the Poisson ratio effect, E_f is the modulus of elasticity of facing skin, t_f is the thickness of the facing skin, h is the distance between the facing skin centres and δ_{fis} the acceptable deflection'.

(b) the facing skin stress:

$$C_6 : \sigma_{f,y} - \frac{k_2 q b^2}{ht} \geq 0 \quad (19)$$

where k_2 is the panel parameter used for simply supported plate;

(c) the shear stress in the core:

$$C_7 : \tau_{f,y} - \frac{k_3 q b}{h} \geq 0 \quad (20)$$

where k_3 is the panel parameter used for simply supported plate;

(d) panel buckling:

$$C_8 : P_{b,cr} - \frac{\pi^2 D}{1^2 + \frac{\pi^2 D}{G_{cor} h b}} \geq 0 \quad (21)$$

where G_{cor} is the core shear modulus in the direction of the applied load and $P_{b,cr}$ is the critical buckling load;

(e) the shear crimping:

$$C_9 : P_{b,cr} - t_{cor} G_{cor} b \geq 0 \quad (22)$$

(f) the skin wrinkling:

$$C_{10} : \sigma_{f,y} - 0.5[G_{cor} E_{cor} E_f]^{1/3} \geq 0 \quad (23)$$

(g) the intracell buckling:

$$C_{11} : \sigma_{f,y} - 2E_f \left[\frac{t_f}{S}\right]^2 \geq 0 \tag{24}$$

(h) the local compression:

$$C_{12} : \sigma_{c,y} - q \geq 0 \tag{25}$$

3.4. Objective Functions

The hybrid structural design considered in this study was a multiple-objective optimisation problem that required the identification of an optimal structural solution to fulfil the established main dimensions of the ship and the defined constraints for steel and AHS structures. The multi-objective optimisation problem produced solutions part of the Pareto frontier [26], and NSGA-II [27] was the algorithm applied to the optimisation procedure to achieve fast and accurate problem solutions aimed to minimise ship costs, lightship weight, and transportation costs while maximising the annual cargo and ultimate ship hull strength.

The objective functions are defined as:

$$F_1 = \min\{\text{Light} - \text{weight}\} \tag{26}$$

$$F_2 = \min\{\text{Ship Cost}\} \tag{27}$$

$$F_3 = \min\{\text{Transportation Cost}\} \tag{28}$$

$$F_4 = \max\{\text{Annual Cargo}\} \tag{29}$$

$$F_5 = \max\{\text{Ultimate Strength}\} \tag{30}$$

The concept design parametric model developed in [18] was employed to define parametric models for the visibility, free-board [28], initial stability [29], bow and stern design [29,30], resistance and propulsion [31], propeller system engine match [32], control and manoeuvrability [33], seakeeping [34], strength [35] and energy efficiency index [36].

The $\{\text{Light} - \text{weight}\}$ was defined using a regression equation based on a statistical analysis of existing ships [37] adapted to the current study, accounting for the hybrid design solution [19] involving AHS. The newly introduced relationship is:

$$LW = 0.034L^{1.7}B^{0.7}D^{04}{C_B}^{0.5}\left(0.2 + 0.8\frac{W_{AHS,steel}}{W_{Steel}}\right) \tag{31}$$

where W_{AHS} is the weight of the 1 m of the hybrid midship section, built from AHS and steel, and W_{Steel} is the weight of 1 m of the midship section built only from steel.

Parameter cost estimates were based on design parameters such as ship size, weight, and horsepower. The $\{\text{Ship Cost}\}$ was estimated based on the annual operating, capital, and decommissioning costs. The capital and operational were used to define [38] the required fright rate. Operating and capital expenditure costs are related to changes that appear to be fixed costs, e.g., inflation and policy changes. Variable costs depend on every voyage, especially the ports, distance, and cargo. The $\{\text{Transportation Cost}\}$ (€/tonne/year) was estimated as a ratio of the discounted annual average cost by the annual cargo capacity.

The assessment of the longitudinal strength of the ship hull structure subjected to vertical bending was based on estimating the maximum bending moment that may act on it. A widely accepted method for evaluating the ultimate strength of a ship hull structure that is that of progressive collapse [39], which considers the effect of the buckling collapse of compressed members. The $\{\text{Ultimate Strength}\}$ of ship hull structure in sagging loading conditions in the present study was calculated based on a compressive strength factor for the most critical panel of the ship hull structure using the relationship suggested by the International Ship Structure Congress [40] and defined as:

$$\varphi_{cr} = \left(0.960 + 0.765\lambda^2 + 0.176\beta^2 + 0.131\lambda^2\beta^2 + 1.064\lambda^4\right)^{-0.5} \tag{32}$$

where:

$$\lambda = \frac{l}{r\pi}\sqrt{\frac{\sigma_y}{E}} \tag{33}$$

$$\beta = \frac{b}{t}\sqrt{\frac{\sigma_y}{E}} \tag{34}$$

$$\sigma_u = \left(-0.172 + 1.548\varphi_{cr} - 0.368\varphi_{cr}^2\right)\sigma_y \tag{35}$$

where λ and β are stiffener and plate slenderness, respectively, and r is the radius of gyration.

The equivalent to steel thickness, flexural, and shear modulus are defined for AHS as follows [41]:

$$t_{eq} = \sqrt{3h_C^2 + 6h_C t_f + 4t_f^2} \tag{36}$$

$$E_{eq} = \frac{2t_f}{t_{eq}} E_f \tag{37}$$

$$G_{eq} = \frac{2t_f}{t_{eq}} G_f \tag{38}$$

4. Multiple Criteria Ship Hull Structural Design Solution Analysis

Nowadays, designer practice considers various solutions across multiple performance metrics, so the multiple criteria decision-making MCDM approach is broadly used. MCDM involves the selection of the "best" alternative from pre-specified options according to a set of various objectives [42–44], and the other options are a finite or infinite number set with multiple equality- and inequality-type constraints in the decision space [45–48].

Two artificial alternatives were analysed using the approach presented in [28]: the ideal alternative with the best scores for all design solutions and the ideal harmful choice, which considers the worst criteria scores. The analysis led to an alternative closest to the ideal positive solution and the farthest from the harmful ideal alternative.

A double-hull bulk carrier with a length of 224.50 m, a beam of 40.70 m, a depth of 20.00 m, a draft of 14.60 m, a block coefficient of 0.85 and a ship speed of 13.00 knots was designed [19] as a hybrid structure, and the midship section can be seen in Figure 1.

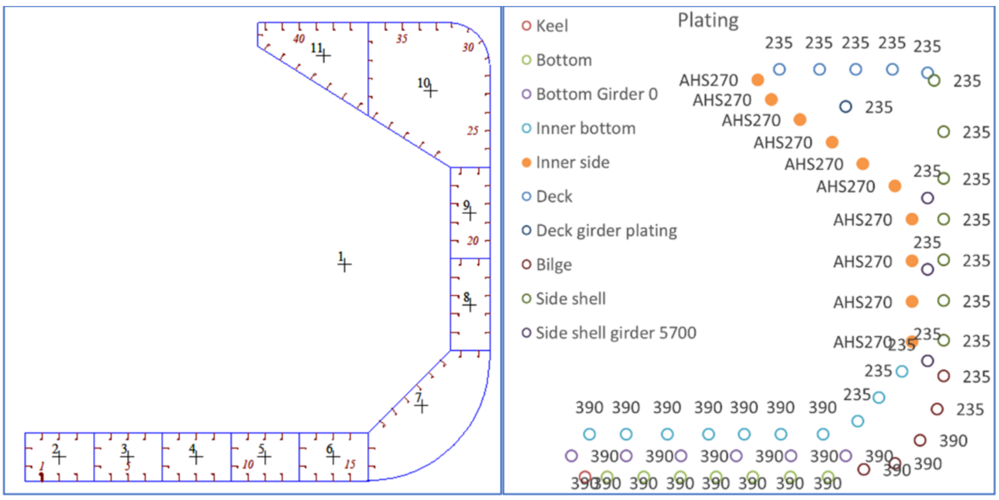

Figure 1. Bulk carrier midship section.

Standard shipbuilding steels were used to construct the midship section from 235 to 390 MPa of yield strength. The assumed unit material cost was 800 €/tonne, and the assumed unit building cost was 1200 €/tonne.

AHS of aluminium alloy 5251-T3 replaced the steel plate of the bulk carrier's inner side shell's cargo hull, creating a hybrid structure together with designed supporting longitudinal stiffer reinforcements [19]. The cost of face-sheet material per unit volume was assumed to be 200 €/m^3, and the cost of honeycomb core material per unit volume was 20 €/m^3. The density of the face sheet was 1.35 kg/m^2 for the fly thickness of 0.5 mm, and the density of the honeycomb core was 83 kg/m^3. The allowed max deflection assumed here was 9.50 mm. The cell size was 6 mm. The yield of facing skin strength was 2.70×10^8 Pa, the yield of the core shear strength was 1.50×10^6 Pa, and the yielding core compression strength was 4.60×10^6 Pa. The core shear modulus in the direction of applied loads was 2.20×10^8 Pa, and the core shear modulus in the ribbon direction was 4.40×10^8 Pa. The core shear modulus in the transverse direction was 20×10^8 Pa, the compression modulus of the core was 1.00×10^9 Pa, and the modulus of elasticity of the facing skin was 7.00×10^{10} Pa. The Poisson's ratio of the face material was 0.33.

The discussed analysis included three alternative design solutions: DS_1—hybrid ship structural design of AHS inner side and remaining ship hull comprising steel, with the reduced light-weight of the ship hull structure being used for additional cargo to be transported; DS_2—ship structural design, where the entire ship hull structure comprises steel; DS_3—hybrid ship structural design of AHS inner side and remaining ship hull comprising steel (see Table 2).

Table 2. Ship design bulk carrier solutions.

Variables:	**DS_1**	**DS_2**	**DS_3**
Length, L, m	224.50	224.50	224.50
Beam, B, m	40.70	40.70	40.70
Depth, D, m	20.00	20.00	20.00
Draft, T, m	14.60	14.60	14.36
Block Coefficient, Cb	0.85	0.85	0.85
Ship Speed, knots	13.00	13.00	13.00
Lightweight, t	14,268.04	16,106.87	14,262.26
Annual Cargo, t	834,468.95	776,603.61	828,145.91
Steel Weight, t	11,977.24	13,816.06	11,977.24
Outfit Weight, t	1,698.17	1698.17	1698.17
Displacement, t	116,226.83	116,226.83	114,342.04
Propulsion Power, kW	8628.46	8628.46	8534.93
Deadweight, t	101,958.79	100,119.97	100 079.78
Daily Fuel Consumption, t	39.55	39.55	39.12
Cargo Deadweight, t	100,488.69	84,839.59	98,624.56
Port Days	26.12	22.21	25.66
Round Trips per Year	8.30	9.15	8.40
Ship Cost, €	18,721,159.38	20,717,152.62	18,683,007.96
Annual Cost, €	6,100,450.23	6,595,162.89	6,083,896.39
Required EEDI	3.16	3.20	3.17
Attained EEDI	2.76	2.78	2.77

If the entire life-cycle of a ship is considered, the economic and sustainability aspects of dismantling activities may be affected by the initial ship design phase. As Ozturkoglu et al. [49] suggested, an efficient design approach should not neglect such aspects.

Considering the framework provided in the previous section, the multi-criteria decision-making routine was enriched by evaluating the ship dismantling impact in economic and environmental sustainability terms. A typical ship dismantling process sequence was defined in [50] as the removal of "non-metal materials" (e.g., electrical components, fuels, and fire hazards) from the ship and the preparation of the surfaces for cutting, the cutting of large ship sections and disassembly, the cutting of large ship sections into smaller sections, and collecting recycling materials.

The ship dismantling phase was assumed to be the same for all case studies. Decommissioning expenditure is only related to a ship's weight through a proper cost model. It does not depend on the type of raw material the ship uses (e.g., steel or aluminium). The sustainability-related aspects of ship manufacturing and dismantling processes are only related to the weight of the ship's raw materials (e.g., steel or aluminium).

The dismantling cost was evaluated for all case studies according to the definition provided by Creese et al. [51]:

$$DC = 12\,738 \frac{FBLR}{45} LSW^{-0.4909} SCF \tag{39}$$

where DC is the dismantling cost, €/tonne; FBLR is the fully burdened labour rate, €/tonne; LSW is the light-weight of the ship, tonnes; and SCF is the ship complexity factor, which was established to be equal to 1 for cargo/merchant ships [51]. Even though the original Equation (39) was reported in US$ units, the results were transformed into €. The average FBLR, as reported in [51], was set to 42.3 €/hr. The reference data for LSW and the resulting dismantling costs for the considered case studies are reported in Table 3. It is worth mentioning that DS_1 and DS_3 were equivalent in terms of structural materials. Therefore, a comparative analysis of DS_1 and the above-mentioned assumptions regarding the dismantling phase was conducted.

Table 3. Dismantling costs for the evaluated design alternatives.

	DS_1	**DS_2**
Steel weight, tonne	8784.65	11,052.85
Aluminium weight, tonne	429.38	/
DC, €/tonne	135.5	124.0
DC, €	1,248,907.9	1,370,130.2

As mentioned in Section 2, recycling implies economic revenues from scrap selling. The profits resulting from selling recyclable materials, according to the data reported in Section 2, could be subtracted from the dismantling costs to obtain a dismantling–reselling cost, DRC, which considers the scrap cost obtained during the dismantling process:

$$DRC = DC - R_A W_{As} - R_S W_{Ss} \tag{40}$$

where W_{As} is the saleable aluminium weight and W_{Ss} is the commercial steel weight. The DRC was evaluated for the DS_1 and DS_2 cases for the same reasons stated in the dismantling costs analysis. The percentage of recyclable and thus saleable materials for both steel and aluminium was assumed to be 70% of the original weight, similar to the values reported in [23]. The reference data applied for the evaluation and the results of the DRC analysis are summarised in Table 4.

Table 4. Dismantling revenues for the analysed case studies.

	DS_1	**DS_2**
% Saleable materials	70%	70%
Saleable steel weight, tonne	6149.3	7737.0
Saleable aluminium weight, tonne	300.6	-
DRC, €	−2,193,340.2	−1,538,979.9

Following the work of Choi et al. [23], reselling scraps from ship decommissioning could generate economic profits for sellers. According to the obtained results, implementing a recycling process for the raw materials of the proposed hybrid solution could increase the profit by approximately 30% compared to the traditional complete steel solution.

The environmental impact of the proposed ship design cases was evaluated considering the energy and the carbon footprint related to raw materials' direct manufacturing (primary production) and their recycling process (secondary production). The analysis considered the following two main scenarios: A—the raw materials from which the ship was made were obtained through direct manufacturing; B—the raw materials from which the ship was made were obtained through recycling.

A comparison of the A and B scenarios allowed for the identification of the best design and manufacturing solution accounting for the entire ship's life-cycle. To evaluate the potential benefits that may arise from a hybrid design solution and the implementation of a sustainable life-cycle process, including recycling, several cases were considered: Case 1—steel ship realized through primary production, i.e., no recycling was performed for raw materials' manufacturing; Case 2—hybrid ship realized through primary production, i.e., no recycling was performed for raw materials' manufacturing; Case 3—steel ship realized through secondary production, i.e., recycling was applied for raw materials' manufacturing; and Case 4—hybrid ship of secondary output, i.e., recycling was used for raw materials' manufacturing.

For Cases 1 to 4, the energy consumption (E_{Pi}) for the raw material manufacturing processes and their carbon footprint (C_{Pi}) were estimated as (see Table 5) follows:

$$E_{P1} = W_S \, E_{p_{steel}} \tag{41}$$

$$C_{P1} = W_S \, C_{p_{steel}} \tag{42}$$

$$E_{P2} = W_S \, E_{p_{steel}} + W_A \, E_{p_{Al}} \tag{43}$$

$$C_{P2} = W_S \, C_{p_{steel}} + W_A \, C_{p_{Al}} \tag{44}$$

$$E_{S3} = W_S \, E_{s_{steel}} \tag{45}$$

$$C_{S3} = W_S \, C_{s steel} \tag{46}$$

$$E_{S4} = W_S \, E_{s_{steel}} + W_A \, E_{s_{Al}} \tag{47}$$

$$C_{S4} = W_S \, C_{s_{steel}} + W_A \, C_{s_{Al}} \tag{48}$$

where W_S is the steel weight and W_A is the aluminium weight.

Table 5. Comparison of different solutions for ship manufacturing.

Case	Description	Energy Consumption, E_{pi}, MJ	Carbon Footprint, C_{pi}, tonnesCO_2
1	Complete steel solution (primary production)	242,057,415	21,774
2	Hybrid solution (primary production)	192,383,835	23,017
3	Complete steel solution (secondary production)	129,318,345	7737
4	Hybrid solution (secondary production)	104,927,305	6407

It can be noticed from Table 5 that the production of the hybrid solution (Case 2), considering the primary processes, required the highest energy and had the highest carbon footprint. This could be explained by the requirements related to aluminium manufacturing processes. However, if a sustainable ship life-cycle is implemented (in agreement with the current dismantling regulations), i.e., the ship is manufactured from recycled raw materials, the benefits are satisfactory. In particular, the hybrid design solution (Case 4) was found to save 19% of energy and costs and 17% of carbon footprint compared to the steel ship (Case 3). Moreover, the sustainable hybrid solution, Case 4, was found to save 57% of energy and 71% of carbon footprint compared to steel ship from primary production (Case 1). Therefore, it can be concluded that the proposed hybrid design and manufacturing solution have high potential benefits in both economic and environmental sustainability terms. Moreover, the obtained results could be helpful for future developments of design procedures addressed at limiting ship life-cycle costs and carbon footprints concerning the construction processes.

The impact of the two sets of design parameters on the ship's structural design solution was analysed using the multiple criteria decision-making Technique of Order Preference by Similarity to Ideal Solution (TOPSIS) [52]. Two artificial alternatives were compared: the ideal option, the best level for all attributes considered, and the perfect negative option, which had the worst attribute values. The TOPSIS method enabled the identification of the closest to the ideal solution and farthest from the ideal negative alternative.

The first set included parameters related to the cost and cargo transportation efficiency, such as C_{11}—capital cost; C_{12}—voyage cost; C_{13}—yearly operating cost; C_{14}—energy efficiency, which was defined as attained EEDI; C_{15}—ship dismantling cost; and C_{16}—cargo transportation.

The ship's total cost was defined as a sum of the capital cost, yearly operating cost, and decommissioning costs. The capital cost was defined as the sum of all costs of building the vessel. The yearly operating cost was defined as the sum of the salary of crew members, expenses related to the stores and supplies, insurance, port expenses, and annual fuel cost.

The second set of design parameters included parameters related to the energy consumption and carbon footprint, such as C_{21}—energy consumption (primary production); C_{22}—energy consumption (secondary production); C_{23}—carbon footprint (primary production); and C_{24}—carbon footprint (secondary production).

Three design scenarios were analysed: D_1—design (Design solution 1) for a dismantling cost and cargo transportation efficiency, where inverse calculations were made to identify the significance of the design criterion that would make the design for cost efficiency the most favourable scenario; D_2—design (Design solution 2) for voyage cost and energy efficiency, where inverse calculations were made to identify the significance of the design criterion that would make the voyage cost and energy efficiency the most favourable scenario; and D_3—design (Design solution 3) for dismantling and capital cost, where inverse calculations were made to identify the significance of the design criterion that would make the dismantling and capital cost the most favourable scenario.

Any ship structural design solution $i = 1, \ldots 3$ is a function of the design criteria that is scored (x_{ij}) concerning the criterion $j = 1, \ldots 6$, where a matrix $\mathbf{X} = \left(x_{ij}\right)$ of $n \times m$ is developed. C_{11} to C_{2m} are defined based on the ship design, scantling, and strength analysis.

$\mathbf{J}^+$ is the set of benefit criteria, where a more significant score represents a better condition. $\mathbf{J}^-$ is the set of negative criteria, where a lower score represents a better condition.

Here, the first step in the analysis was to construct a normalised decision matrix, where the criterion dimensions were transformed into non-dimensional ones [53]:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum x_{ij}^2}} \tag{49}$$

Next, the weighted normalised decision matrix was constructed using a set of weights for each criterion w_j, where each column of the normalised decision matrix is multiplied by its associated weight:

$$v_{ij} = w_j r_{ij} \tag{50}$$

The positive ideal solution is defined by:

$$A^* = \{v_1^*, \ldots, v_m^*\} \tag{51}$$

where $v_j^* = \left\{\max\left(v_{ij} \text{ if } j \in \mathbf{J}^+, \ \min\left(v_{ij}\right) \text{ if } j \in \mathbf{J}^{+'}\right)\right\}$ and the negative ideal solution is defined as:

$$A^* = \left\{v_1^{'}, \ldots, v_m^{'}\right\} \tag{52}$$

where $v'_j = \left\{ \min\left(v_{ij} \text{ if } j \in \mathbf{J}^-,\ \max\left(v_{ij} \right) \text{ if } j \in \mathbf{J}^{-'} \right) \right\}$.

The separation measures for each alternative are defined as:

$$S_i^* = \left[\sum \left(v_j^* - v_{ij} \right)^2 \right],\ i = 1,\ \ldots,\ n \quad (53)$$

$$S'_i = \left[\sum \left(v'_j - v_{ij} \right)^2 \right],\ i = 1,\ \ldots,\ n \quad (54)$$

The relative closeness to the ideal solution C_i^* is calculated as:

$$C_i^* = \frac{S_i^*}{S_i^* + S'_i} \text{ for } 0 < C_i^* < 1 \quad (55)$$

The inverse multi-attribute decision-making calculation for any design solution was used to identify the importance of different criteria, quantified by the maximum relative closeness to the ideal solution. In this regard, the weights of all design criteria were initially assumed to be uniformly distributed. At the end of the analysis, the weights were estimated according to the maximum relative closeness to the ideal design solution.

The option with C_i^* that was closest to 1 was the best-suited solution. The significance levels of different criteria for the maximum relative closeness to the ideal solution for the first set of design parameters are presented in Figure 2.

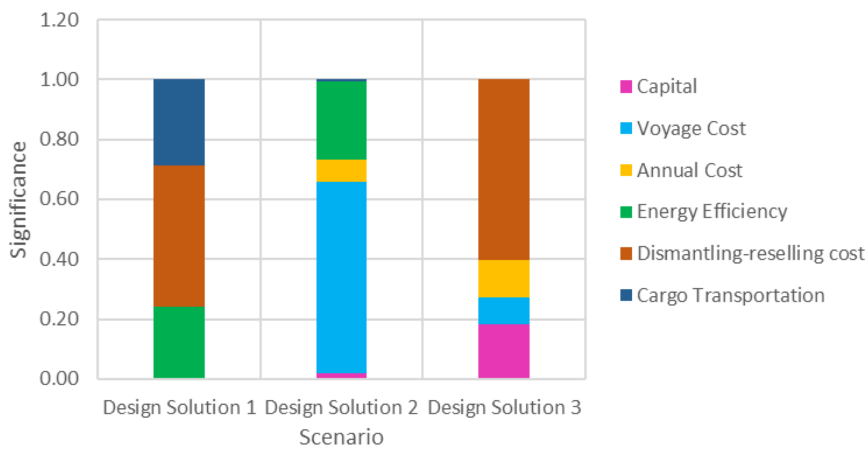

Figure 2. Significance of design criteria for different design solutions.

As can be seen from Figure 2, the best-suited design criteria to be kept in design solution DS_1 (where the hybrid ship structural design of AHS inner side and the remaining ship hull comprised steel and the reduced light-weight of the ship hull structure was used for additional cargo to be transported) resulted in the following significance factors: 47% for dismantling–reselling cost, 29% for cargo transportation and 24% for the energy efficiency estimated here as EEDI.

The ship structural design solution DS_2 totally comprises steel. In this design solution, various design parameters with different significance contributed to make it the best, e.g., 64% voyage cost, 26% energy efficiency, 7% annual cost, 2% capital and 1% cargo transportation.

In the third design solution, which represented a poor hybrid solution, the most significant factors were 60% dismantling, 18% capital, 12% annual cost and 10% voyage cost.

Suppose all involved design parameters were considered the same weight in the multi-criteria decision. The relative closeness to the ideal solution made the first design solution the most acceptable solution at 97%, followed by the third design solution at 95% and the second design solution at 2%.

Since DS_1 and DS_3 were equivalent structural materials, the energy consumption and carbon footprint analyses were performed for the first two design solutions (see Figure 3).

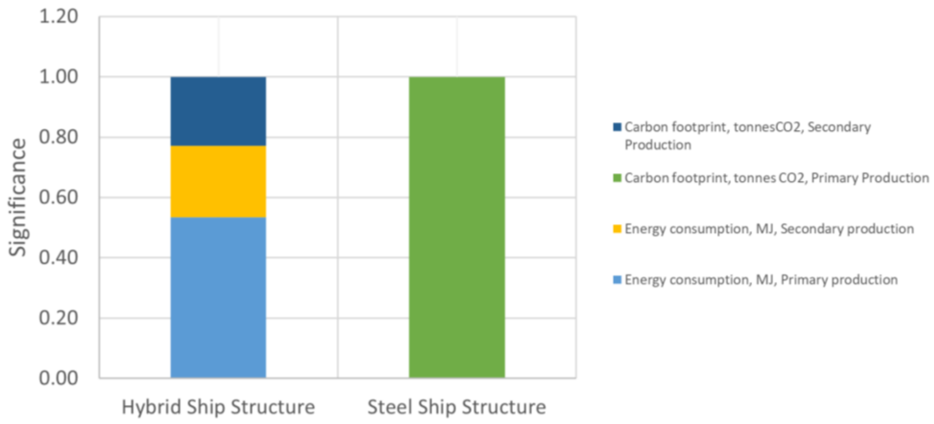

Figure 3. Significance of design criteria for energy consumption and carbon footprint.

It can be noticed from Figure 3 that in the hybrid design solution, the most significant factors were 53% energy consumption (primary production), 24% energy consumption (secondary production) and 23% carbon footprint (secondary production). In the steel ship structure design solution, 100% significance was estimated to carbon footprint in tonnes (primary production).

Suppose all involved energy consumption and carbon footprint were considered the same weight in the multi-criteria decision. The relative closeness to the ideal solution made the hybrid design solution the most acceptable with 87%, followed by the steel ship structure design solution with 13%.

5. Conclusions

The authors of the present study developed a procedure to quantify the potential benefits deriving from the integration of innovative light-weight structures in ship design and manufacturing processes. A bulk carrier was considered as a case study, and the primary design factors of a hybrid light-weight ship hull structural design were evaluated for such application. In particular, the analysis was focused on: capital cost, voyage cost, annual cost, energy efficiency design index, dismantling–reselling cost, cargo transportation, energy consumption and carbon footprint. A comparison was conducted between a traditional steel design solution and a hybrid one utilising light-weight aluminium honeycomb sandwich panels to replace conventional steel-stiffened structures. The evaluation was based on a multiple criteria decision-making approach to identify the optimal design solution. The potential cost and energy saving during ships' construction and operational phases were evaluated, demonstrating that the hybrid structural design, combined with efficiency in cargo transportation, led to the best design solution. Energy efficiency could be gained if the hybrid light-weight ship hull structural design was accompanied by more cargo resulting from light-weight reduction, which led to improvements in the energy efficiency design index, which resulted in 2.76 gCO_2/tonne-mile, and operational costs, which were reduced by approximately 7.5% in comparison to the whole steel design alternative. Additionally, it was proven that aluminium sandwich structures provide a promising solution with less energy consumption and carbon footprint, especially if aluminium from secondary production is utilized for ship manufacturing. In this case, when compared to the whole steel solution, a potential 57% of energy savings and 71% of carbon footprint reductions in the material production process were found.

It can be pointed out that the approach employed in this work clearly identified the most critical design criteria for any specific ship design solution and thus paves the way for the integration of innovative light-weight structures in shipbuilding.

It is worth mentioning that the procedure developed to support the integration of innovative light-weight structures in the maritime sector deals with the concept design phase. This research needs further developments to fine-tune the procedure and target a reliable and sustainable ship design. Among the current limitations, the issue of connecting honeycomb sandwich structures to other steel structural components requires thorough investigation. Though several options, such as bimetallic connections [54], bolted joints [55] and edge joints [56], are available, dedicated analyses of the suggested applications are required. Another matter of utmost importance is the necessity to develop dedicated investigations to verify the local and overall strength of the suggested hybrid solution. Moreover, a more in-depth analysis of the hybrid structure's environmental impact is required. Data related to the ship production process may be utilized to better estimate the benefits derived by implementing a green ship life-cycle.

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