Ocean Engineering 70 (2013) 61–71

Contents lists available at SciVerse ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

A method for comparing panel complexity to traditional material and production cost estimating techniques

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A R T I C L E I N F O

Article history:
Received 14 December 2012
Accepted 11 May 2013
Available online 19 June 2013

Keywords:
Producibility
Genetic optimization
Early stage design
Stiffened panel
Design complexity
Cost assessment

A B S T R A C T

In this paper a metric for assessing the producibility of a stiffened grillage structure in the early stage design is presented. This metric is comprised of seven separate producibility drivers that are dependent on the properties of the panel. The new producibility metric is compared with a traditional costing method in a two-objective genetic algorithm to show that there is a competition between the two methods, meaning that the new metric gives a designer additional information at the early design stage. The estimated costs versus producibility scores for several grillage sizes show that large gains in producibility can be made without large increases in estimated costs up until a critical point where a knee in the Pareto front occurs. Furthermore, it was found that the individual producibility elements are highly dependent on the size of the panel tested and the constraints the panel must meet. In general, producibility is a key factor to be considered in structural design and should be accounted for in any structural optimization.

1. Introduction

Traditional methods for estimating costs of ship structures rely mainly on material costs and weld lengths but often do not formally attempt to assess other producibility criteria, such as complexity or ease of outfit installation, nor do they give explicit producibility feedback to the engineer. Effectively assessing producibility early in the design process is challenging, as details of construction and outfit are typically not known when the initial structural design is created. At the moment, general rules of thumb can be used, or such decisions need to be deferred until a more complete CAD model of the vessel is available. This paper introduces the concept of a simple producibility metric to aggregate existing references and studies on producibility and complexity concepts into a generalized score that can be easily tracked during the early stage design.

Traditional structural cost estimating methods in the marine industry are based on weight and weld length based methods that assume fixed costs of steel and welding consumables and other overhead costs (Baretine, 1996; Rahman and Caldwell, 1995; Ferguson, 1944). Fixed welding rates are used to calculate the work times and therefore the wages paid to the welders. Such approaches have been developed into powerful optimization frameworks to aid in least-cost structural optimization (Rigo, 2001). While material and welding expense can easily be quantified, translating more complex attributes such as curvature, outfit potential, or likely rework requirements into production cost terms remains challenging. However, as designs have gotten more complex and expensive, more focus has been put on designing a producible ship including these factors. In 1993, Bunch produced a catalog of producibility concepts aimed for Navy ships. The concepts in this catalog were more qualitative and gave guidance as to what a producible design would include without any guidance toward weighing material costs versus production costs. Lamb (1994) quantified how the curvature of the hull affects production complexity which was then used to compare alternative hull designs (Parsons et al., 1998). Work has also been done to predict weld distortions (Bruce et al., 2001; Chau et al., 2001) and the costs associated with straightening distortions (Caprace et al., 2009). Broderick et al. (2012) have explored the link between structural complexity and the effectiveness of coating in water ballast tanks. Caprace and Rigo (2012) have attempted to combine all these issues together and create a metric for total ship complexity, which takes into account shape complexity, assembly complexity, and material complexity. The described material complexity factor takes a whole ship approach and is calculated by finding the number of combinations of plate thickness and material type and stiffener type, size and material. In general, design for production or assembly is not a new topic and an overview of research can be found in Kuo et al. (2001).

The aerospace community has followed a similar path in cost estimating. Initially structural costs were estimated based on weight or size (Roskam, 1990; Hess and Romanoff, 1987). As

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0029-8018/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.oceaneng.2013.05.031

higher fidelity estimates were needed, relative complexity and structural material were used to estimate manufacturing hours per aircraft pound of weight (Resetar et al., 1991). These methods did not have the required sensitivity to manufacturing variables so there was a move to feature based costing (Kaufmann et al., 2010). Currently, cost estimators like SEER for manufacturing (Galorath Inc., 2011) are used to estimate the production costs associated with a particular design but approaches like this require a detailed CAD design which is not available at the preliminary design stage. In the civil engineering field research has been completed to estimate construction costs based on structural equation modeling, multiple regression analysis, neural networks, and case-based reasoning to compare new build construction costs to historical costs (Kim et al., 2004; Petroutsatou and Lambropoulous, 2010) but these methods also require a detailed design definition. Son et al. (2011) take a similar approach for estimating the cost of building a new ship but as the cost is derived from previously built ships their approach is not suitable for new or innovative ship designs.

At the present time, early-stage design evaluation can be completed when material, welding, labor and overhead expenses are considered, and more complex producibility evaluations can be carried out when 3-D CAD models are available. However, techniques to include more complex producibility evaluations in the early-stage structural design are largely still confined to the “rule of thumb” approaches such as the producibility catalog of Bunch (1993). This work introduces a new producibility metric that does not rely on a completed three dimensional model, and, therefore, can be used earlier in the design process as a tool for designers to quickly identify potential gains in producibility. This metric is based on the application of utility functions to quantify existing producibility studies, and is applied at the stiffened grillage level. These utility functions attempt to convert linguistic information (good, bad, great, etc.) about various properties of a stiffened grillage into a numeric score that can then be used for multi-objective optimization. A similar strategy was used by Nick (2008) to automate the process of creating general arrangements. Using multi-objective optimization, this metric is compared to existing cost models and shown to include new information that is lacking from the existing costing approaches for a wide range of grillage designs, which indicates that adding a producibility metric to the structural design process can lead to improved structural designs. This paper will begin by introducing the production method and its components. Next will be a description of how the method was tested compared to traditional methods along with the results of the said test. The paper will end with a discussion of the results and present conclusions and recommendations about how this work can be implemented and expanded upon.

2. Producibility metric

The central focus of this work is a new producibility metric applicable to the early-stage grillage design. The new producibility metric developed consists of seven elements which were selected from a much larger set of possible producibility drivers (Rigterink and Singer, 2011). The initial set of drivers was identified by an analysis of the ship construction process and was further refined through discussions with shipbuilders. The authors have attempted to keep this metric as simple as possible which is why only seven elements were chosen for this initial study, although yard or product-specific extensions of this framework are certainly possible. The metric is presented in Eq. (1) and further described in Table 1 and throughout the rest of Section 2. Fig. 1 shows an example stiffened panel with a description of how each producibility driver is measured.

Table 1
Weights for averaging producibility metric.

Coefficient	Description	Weight
P	Producibility score	–
U_x	x-Direction access	w_x
U_y	y-Direction access	w_y
U_{stiff}	Stiffener spacing to panel thickness	w_{stiff}
U_{effect}	Effective panel aspect ratio	w_{effect}
U_{sum}	Joint thickness sum	w_{sum}
U_{ratio}	Joint thickness ratio	w_{ratio}
U_{outfit}	Outfit potential	w_{outfit}

$$P = \frac{w_x U_x + w_y U_y + w_{space} U_{space} + w_{effect} U_{effect} + w_{sum} U_{sum} + w_{ratio} U_{ratio} + w_{outfit} U_{ratio}}{w_x + w_y + w_{space} + w_{effect} + w_{sum} + w_{ratio} + w_{outfit}} \quad (1)$$

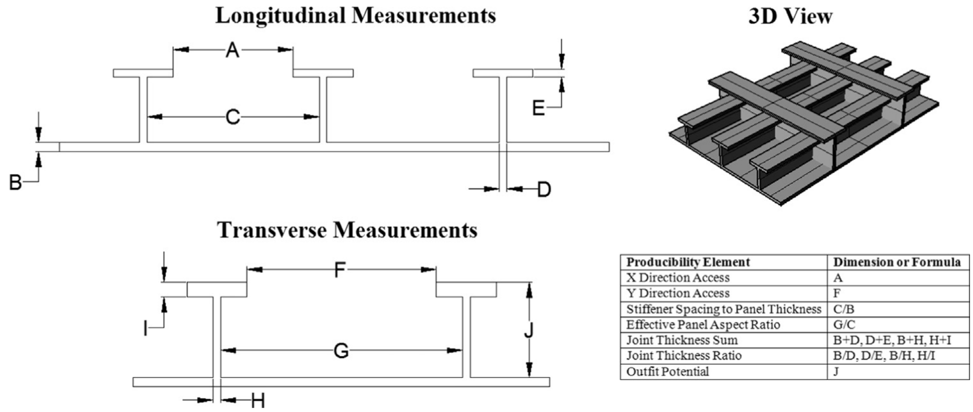
Each element of the metric receives a dimensionless utility score between zero and one. Rather than scoring something on a 0 or 1, yes or no, good or bad scale, the utility functions attempt to provide a more nuanced score. A score of zero is unsatisfactory in terms of producibility whereas a score of one is perfect in terms of producibility. A score of 0.8 might translate to great while a 0.2 might be seen as bad but acceptable. A similar concept was used by Nick (2008) to quantitatively score the preference of compartments to be located near or far from one another in ship arrangements.

The different utility function values in the producibility metric are combined into a single producibility score by finding the average score of the utility function. By using addition in place of multiplication, the proposed metric still provides useful feedback in situations where structural or design constraints require one aspect of the metric to receive a zero utility score. Previously, both weighted and non-weighted averages were examined (Rigterink et al., 2012) but both approaches compared similarly to conventional costing techniques. Weights could be assigned to the utility values depending on shipyard competencies to create a shipyard-specific metric. However, calibration of these weights would be required using past vessel construction cost data. In this study, we focused instead on the comparison of the un-weighted average utility score to conventional cost estimation techniques, as the un-weighted score is the most generic or widely applicable score. The following graphs show the utility functions used in this study. These functions were created from previously published material combined with engineering judgment for a generic shipyard.

2.1. x-Direction and y-direction access

The first two parts of the metric are the x-direction and y-direction access for a shipyard worker to reach between longitudinal or transverse stiffeners and weld. This distance is measured between the nearest edges of the stiffener flanges, i.e., the minimum space a worker would need to reach through in order to weld a piece of outfitting to the base plate. The distance between longitudinal stiffener flanges is the x-direction and the distance between transverse stiffener flanges is the y-direction. The utility function is shown in Fig. 2.

The ease or difficulty of attaching stiffeners to the base plate as well as installing foundations, outfit, and backup structure is considered for this metric. The utility value of zero is based on the minimum distance required for a production worker to fit a welding shield through the flanges with enough clearance to move his or her head in order to get a good view of the weld and operate the welding tool adequately. A review of 95 commercially available



Producibility Element	Dimension or Formula
X Direction Access	A
Y Direction Access	F
Stiffener Spacing to Panel Thickness	C/B
Effective Panel Aspect Ratio	G/C
Joint Thickness Sum	B+D, D+E, B+H, H+I
Joint Thickness Ratio	B/D, D/E, B/H, H/I
Outfit Potential	J

Fig. 1. Example stiffened panel.

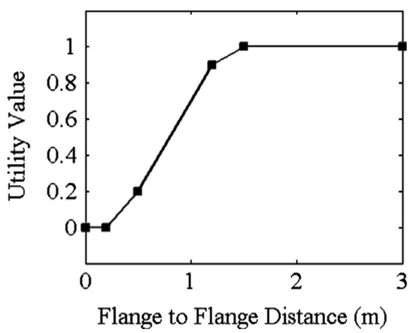


Fig. 2. *x*- or *y*-Direction access utility function.

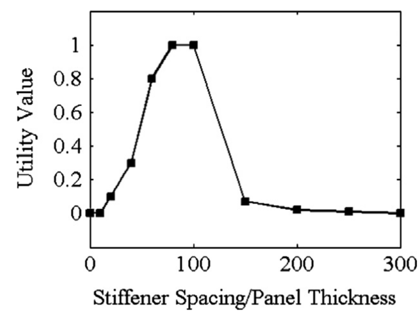


Fig. 3. Stiffener spacing to panel thickness utility function.

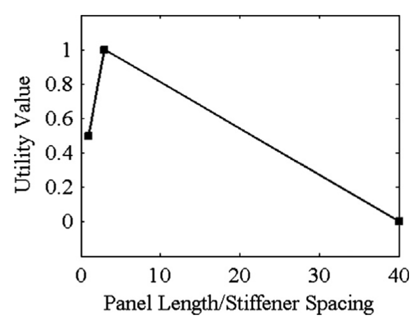


Fig. 4. Effective aspect ratio utility function.

welding masks found the average shield width is 105 mm $\pm$ 6.8 mm (Grainger Industrial Supply, 2012), and to allow for movement, a minimum flange to flange distance of 0.2 m was selected. Above 1.5 m, there is no anticipation of obstruction for any installation process, and any access distance larger than 1.5 m receives a score of one.

2.2. *Stiffener spacing to panel thickness*

A key complexity driver is the susceptibility of the structure to weld-induced distortions which may require straightening or other costly re-work. Longitudinal stiffener spacing on its own does not imply anything with respect to distortion; it becomes a useful metric when the spacing is compared against the thickness of the base plate to which the stiffeners are being welded. When the ratio of stiffener spacing to base plate thickness is small, this implies tight stiffener spacing and/or a thick plate which is undesirable because it requires high heat inputs which could distort the panel or weaken the material in the stiffeners. A large ratio would imply large stiffener spacing and small panel thickness meaning there is minimal stiffening support for the panel, also making buckling distortion more likely. Only longitudinal stiffener spacing is being considered for this metric and the base plate thickness is assumed to be constant for each panel. The utility function for this element is presented in Fig. 3 and was derived from Dydo et al. (1999). Above a ratio of 300, the utility score remains at zero.

2.3. *Effective aspect ratio*

The effective aspect ratio is the ratio of the length of the strake between transverse frames to the stiffener spacing. Essentially, a new panel is made in between each set of stiffeners and transverse frames; therefore, the longer the transverse frame spacing and the narrower the stiffener spacing, the higher the expected residual stresses and more likely the panel is to experience distortion. A square panel (aspect ratio of 1) should also be avoided because it has the same critical buckling strength in two directions (Dydo et al., 1999; Huang et al., 2004). An effective aspect ratio of 3 is the most desirable, and above 3 the longitudinal critical buckling load of the plating begins to decrease (Dydo et al., 1999). This desirability decreases linearly until 40 and above where it has a utility score of zero (Huang et al., 2007). See Fig. 4 for the utility function.

2.4. *Joint thickness sum*

The joint thickness sum metric (Fig. 5) expresses the relative ease or difficulty of making perpendicular filler weld connections between webs and shell or flange plating. It is calculated by taking the total sum of thicknesses for all plate members meeting at a welded joint. This metric has been derived from Part 3, Chapter 2, Section 19 of the American Bureau of Shipping Rules for Building and Classing Steel Vessels (2010). Thinner overall joint thicknesses allow for simple welds that require little preparation, whereas thicker steels require either single or double beveling and larger welds to be effective (United States Department of Defense, 1974).

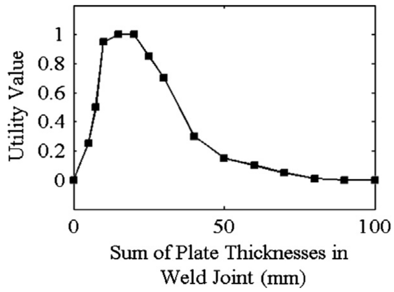


Fig. 5. Joint thickness sum utility function.

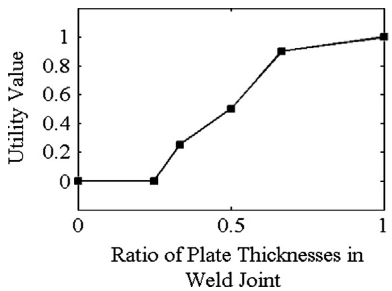


Fig. 6. Joint thickness ratio utility function.

Both beveling and drawing larger welds require more time and are therefore less producible. Above a sum of 100 mm, the utility function is zero. Welding of very thick plates (50 mm plus) also can lead to brittle cracking along the weld seams and to substantial rework or more serious failures (Schipperen et al., 2012). The four joints considered for this utility function as well as the joint thickness ratio are base plate to longitudinal web, base plate to transverse web, longitudinal web to longitudinal flange, and transverse web to transverse flange. The total thickness of the plate butt welds required to create the base plate could also be factored into this element but was not in this paper as the base plate thicknesses were roughly equal for the individual panels of a given size.

2.5. Joint thickness ratio

The joint thickness ratio is calculated by dividing the smaller plate thickness in a weld joint by the larger plate thickness. This metric (Fig. 6) expresses the ease or difficulty of joining two plates based on their relative sizes. Beveling is typically required for size ratios below 0.5. It is generally assumed that the more extreme the thickness ratio, the more likely the thinner plate is to experience distortion. This metric does not account for two thick plates of nearly equal thickness being joined though beveling. The complexity of that case is covered by the joint thickness sum utility function discussed in Section 2.4. Below a ratio of 0.25 the utility score is zero as the heat input into the smaller plate will cause significant distortion and/or weakening in the heat-affected zone; extreme ratios should be avoided.

2.6. Outfit potential

This metric expresses the difficulty of running pipes, cables, or ventilation shafts through a stiffened unit. The trade-off represented is whether: the outfit can be run straight over the transverse webs; the outfit needs to be bent using elbows to fit in between the traverse webs; or penetrations need to be cut in the transverse webs to run the outfit through. It is understood that this function is dependent upon the size of the pieces to be outfitted and thus can be adapted on a per-vessel basis; for the

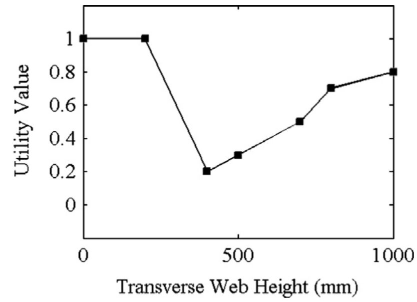


Fig. 7. Outfit potential utility function.

current example, a 0.1 m diameter pipe has been assumed. In this utility function (Fig. 7):

- The pipe would be straight and placed over the transverse stiffeners if they are less than or equal to 0.2 m;
- For transverse webs between 0.2 m and 0.4 m, elbows will need to be used to snake the pipe between transverse stiffeners. Elbows would be required because the transverse stiffeners are not large enough to support penetrations;
- Above 0.4 m transverse webs, penetrations will need to be cut; and
- Beyond 1 m transverse webs, the utility function is 0.7, as even easy cutting still requires more work than simply running the outfit above the girders.

This utility function assumes penetrations are cut automatically via numerically controlled cutting. If the penetrations are cut manually, the utility function for transverse webs taller than 0.4 m will increase at a slower rate as manual cutting is a slower and more costly process than automated cutting. If more data were available in regards to other pipes, HVAC ducts, or electrical wires a series of more detailed utility functions could be created. HVAC ducts for example would prefer smaller stiffeners so they can be simply run over the stiffeners instead of bending around them, whereas electrical wires can easily be around stiffeners but this requires more wire leading to extra weight. These additional utility functions could be simply averaged into the overall producibility score.

3. Comparison with traditional costing method

The developed producibility metric was compared to a traditional costing function using a two objective genetic optimization algorithm to determine if there is competition between the two metrics, indicating that the new production metric is adding information to the early-stage structural design problem. A series of grillages consisting of a plate, longitudinal, and transverse stiffeners is created and then optimized according to these two competing criteria.

3.1. Rahman and Caldwell cost model

For comparison, the costing methodology presented by Rahman and Caldwell (1995) was used as the traditional costing approach, as this methodology has formed the basis of many studies into structural optimization (e.g. Rigo, 2001). As used here, the original methodology has been modified to apply to a single cross-stiffened grillage and was used to predict the total cost, C in Eq. (2). The optimizer attempts to minimize this equation as one of

Table 2
Components of the cost model.

Coefficient	Description	Formula
C_{plate}	Cost of materials for plating	W_pP_a
C_{stiff}	Cost of materials for stiffeners	$(W_lC_{lm}+W_tC_f)P_a$
C_{weld}	Cost of welding for stiffeners	$(N_lLC_{ls}+2N_tBC_{wf})P_s$
$C_{intersect}$	Cost of intersections between longitudinal stiffeners and transverse frames and preparation of brackets and joints	$N_lN_t(C_{bj}+C_{is})P_s$
$C_{electric}$	Cost of electricity, electrodes and fabrication cost of longitudinal stiffeners	$(N_lL+2N_tB)(C_{ee}+C_{fb})P_s$

Table 3
Coefficients of the cost model.

Coefficient	Description	Value	Unit
W_p	Weight of plate	–	ton
P_a	Material price	700	U.S. $/ton
W_l	Weight of longitudinal stiffeners	–	ton
C_{lm}	Increase cost of longitudinal stiffeners	1.05	Coefficient
W_t	Weight of transverse stiffeners	–	ton
C_f	Increase cost of transverse stiffeners	1.4	Coefficient
N_l	Number of longitudinal stiffeners	–	Pieces
L	Panel length	–	m
C_{ls}	Labor required for welding longitudinal stiffeners to plate	–	h/m
N_t	Number of transverse stiffeners	–	Pieces
B	Panel breadth	–	m
C_{wf}	Labor required for welding transverse stiffeners to plate	–	h/m
P_s	Labor rate	27	U.S. $/h
C_{bj}	Labor required connecting stiffeners to transverse frames	0.6	h
C_{is}	Labor required for welding stiffeners to transverse frames	1.15	h
C_{ee}	Labor-equivalent cost for welding supplies and consumables	0.9	h
C_{fb}	Labor required for fabrication on stiffeners	1.5	h

Table 4
Panel Cost Breakdown.

Cost element	Cost	Percent of total cost (%)
Base plate material	\$1080	12
Longitudinal stiffener material	\$1795	20
Transverse stiffener material	\$2379	27
Longitudinal welding cost	\$694	8
Transverse welding cost	\$504	6
Intersection cost	\$473	5
Electricity cost	\$2009	22
Total	**\$8934**	

Table 5
Upper and lower bounds of panel parameters.

Parameter (mm)	Lower bound	Upper bound
Longitudinal stiffener spacing	300	900
Transverse stiffener spacing	1000	3500
Plate thickness	5	75
Longitudinal web thickness	5	50
Longitudinal web height	50	1500
Longitudinal flange thickness	5	75
Longitudinal flange breadth	25	500
Transverse web height	50	1500
Transverse web thickness	5	75
Transverse flange thickness	5	75
Transverse flange breadth	25	750

its two objective functions.

$$C = C_{plate} + C_{stiff} + C_{weld} + C_{intersect} + C_{electric} \tag{2}$$

The structure and coefficients of Eq. (2) are presented in Tables 2 and 3

The labor required for welding the longitudinal and transverse stiffeners to the plate varies between 1.2 h/m and 3.6 h/m and is proportionate the throat size of the weld which is based on the thinner of the two plates in the joint. The costs for the panels found in this optimization are approximate and serve to show the relative cost differences between different designs. The rates and costs would need to be tailored for specific shipyards. Table 4 shows the breakdown of costs for 5 m × 4 m panel.

3.2. Optimization model

The NSGA-II multi-objective algorithm optimizer (Deb et al., 2002) is used in this optimization problem. The NSGA-II algorithm is an elitist genetic algorithm that uses non-dominated sorting to rank candidate solutions in sequential non-dominated fronts within each generation of the algorithm. When it is necessary to choose between members of the same front, a crowing distance metric is used. In this problem, children are created from parent chromosomes by both crossover and mutation. For the cases studies here, a population size of 100 individuals was used, with 450 generations. The simulated binary crossover (Deb, 2001) algorithm is used for crossover with an exponent of 2. Random mutation is applied with a probability of occurrence of 1.0%.

To study the impact of grillage size on the new producability metric, five different sized grillages were examined: 8 m × 16 m (longitudinal length by transverse length) panel representing a large commercial vessel; a 10 m square panel; a 5 m × 4 m panel respresenting a piece of structure in a Navy vessel; a 5 m × 2 m panel representing a piece of structure in a small high-speed craft; and a 2 m × 5 m panel. For each panel, the optimization problem configuration was the same. The independent variables are: longitudinal stiffener spacing (n_l); transverse stiffener spacing (n_t); main plate thickness (t_p); longitudinal and transverse web thicknesses (t_{lw} and t_{tw}, respectively); longitudinal and transverse web heights (h_l and h_t, respectively); longitudinal and transverse flange thicknesses (t_{lf} and t_{tf}, respectively); and longitudinal and transverse flange breadths (b_l and b_t, respectively). The ranges for these variables are listed in Table 5.

The length, width, and material of the panel are held constant during the optimization. The tested panels were made of A36 steel. The bounds were kept the same across all panels.

3.3. Constraints

Strength is used as the constraint on each candidate grillage to limit the members of the final Pareto front to grillages representative of the marine structural design. Longitudinal compressive strength is evaluated using the formulation proposed by Faulkner et al. (1973) for panel strength. This formulation idealizes a single tee-stiffener and attached plate between transverse frames as a beam-column and ignores any support from the longitudinal girders at the panel edge. When there is no tripping, the Faulkner formulation is an iterative Johnson–Ostenfeld column formulation that has been modified to account for plate buckling on both the effective width of the plate and the overall column stiffness. These effects are accounted for by modifying the elastic column slenderness parameter to become a function of the current applied edge stress. The stiffener tripping stress is calculated separately using the method proposed by Faulkner (1987). The lower of the panel buckling and tripping stress ($\sigma_{buckling}$ and $\sigma_{tripping}$, respectively) is taken as the governing stress. For this work, the constraint was set so that each panel must achieve a compressive ultimate strength of at least 200 MPa, which corresponds to 80% of the material's yield stress. For most stiffened shell structures the compressive buckling strength of the panel is the critical driver of panel dimensions. The resulting panels were spot-checked for stiffener yielding from lateral pressure and the maximum stresses were found to be in the 50 MPa range, meaning yielding is not a concern.

In the transverse direction, the grillage was required to meet local buckling and bending requirements set forth in the American Bureau of Shipping Rules for High-Speed Naval Craft (2006). Subsection 1.5.6 of Part 3, Chapter 2, Section 4 gives requirements for the height of transverse webs (Eq. (3)) and the breadth of transverse flanges (Eq. (4)) to prevent local buckling. The coefficients of these equations are shown in Table 6.

$$\frac{h_t}{t_{tw}} \leq 1.5\left(\frac{E}{\sigma_y}\right)^{1/2} C_2 \quad (3)$$

$$\frac{b_t}{t_{tf}} \leq 0.5\left(\frac{E}{\sigma_y}\right)^{1/2} C_2 \quad (4)$$

Subsection 1.3.1 of Part 3, Chapter 2, Section 4 gives the requirement on section modulus of the transverse stiffeners (Eq. (5)), the coefficients are shown in Table 7.

$$SM \geq \frac{83.3 \times psl^2}{\sigma_a} \quad (5)$$

Three additional constraints were placed on various stiffener rations. The transverse web is required to be at least twice the height of the longitudinal web, the longitudinal web height can be no more than five times the longitudinal flange breath, and the transverse web height can be no more than two and a half times the transverse flange breadth. In the NSGA-II algorithm, any feasible solution (ones without constraint violations) is considered superior to any infeasible solution. The infeasible solutions are ranked based on the severity of their constraint violations.

The full optimization problem is written in Eq. (6) with the sign changed on the producibility score to facilitate a minimization problem even though the goal is to maximize the producibility score.

$$\text{Minimize}: f(\tilde{x}) = (C, -P)$$

$$\text{By varying}: \tilde{x} = (n_l, n_t, t_p, t_{lw}, t_{tw}, h_l, h_t, t_{lf}, t_{tf}, b_l, b_t)$$

$$\text{Subject to}: \min(\sigma_{buckling}, \ \sigma_{tripping}) \geq 200 \text{ MPa}$$

$$\frac{h_t}{t_{tw}} \leq 1.5\left(\frac{E}{\sigma_y}\right)^{1/2} C_2$$

$$\frac{b_t}{t_{tf}} \leq 0.5\left(\frac{E}{\sigma_y}\right)^{1/2} C_2$$

$$SM \geq \frac{83.3 \times psl^2}{\sigma_a}, \quad h_t \geq 2h_l, \quad h_l \leq 5b_l, \quad h_t \leq 2.5b_t \quad (6)$$

Table 6
Coefficients of transverse web and flange local buckling equations.

Coefficient	Description	Value	Unit
h_t/b_t	Height of web or breadth of flange	Varies	mm
$t_{tw/tf}$	Total required thickness of web or flange	Varies	mm
E	Young's modulus	200	GPa
σ_y	Yield strength	250	MPa
C_2	Coefficient	1	–

Table 7
Coefficients of section modulus equation.

Coefficient	Description	Value	Unit
SM	Section modulus	Varies	cm^3
p	Design pressure	75	kPa
s	Transverse stiffener spacing	Varies	m
l	Length of transverse web between supports	Varies	m
σ_a	Allowable stress ($0.8\sigma_y$)	200	MPa

Table 8
Range of Pareto fronts.

Panel ($L \times W$)	Lowest cost		Highest producibility	
	Producibility Score	Estimated Cost/m^2	Producibility Score	Estimated Cost/m^2
8 m × 16 m	0.727	$433.33	0.757	$435.51
10 m × 10 m	0.735	$439.27	0.755	$458.14
5 m × 4 m	0.628	$373.99	0.793	$446.71
5 m × 2 m	0.796	$352.27	0.809	$359.72
2 m × 5 m	0.731	$434.67	0.778	$469.83

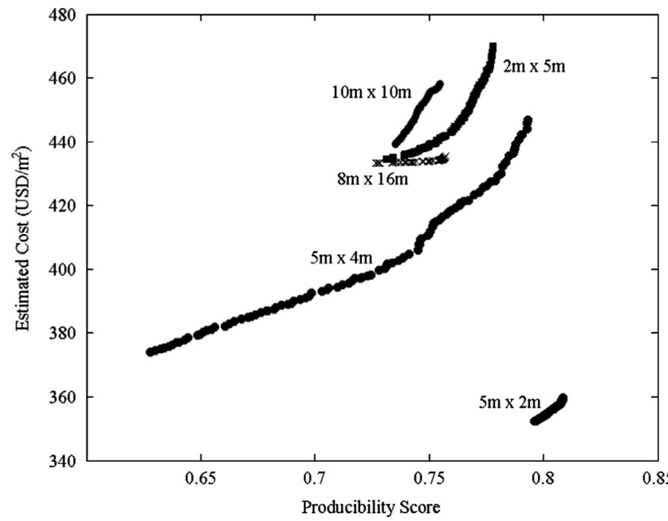


Fig. 8. Pareto fronts normalized for cost per square meter.

Table 9
8 m × 16 m and 5 m × 4 m panel properties.

Parameter	8 m × 16 m			5 m × 4 m		
	Lowest cost	Mid-range	Most producible	Lowest cost	Mid-range	Most producible
Production score	0.727	0.753	0.757	0.628	0.730	0.793
Estimated cost ($)	55,467	55,562	55,744	7480	8005	8934
Normalized cost ($/m^2)	433	434	435	373	400	447
Number of longitudinal Stiffeners	32	32	32	5	5	5
Number of transverse Stiffeners	2	2	2	2	2	2
Plate thickness (mm)	5.0	5.0	5.0	5.0	6.6	8.0
Longitudinal web thickness (mm)	7.2	7.2	7.2	11.5	11.4	12.0
Longitudinal web height (mm)	238.2	238.2	238.2	174.2	216.7	287.4
Longitudinal flange thickness (mm)	21.4	21.3	21.3	23.1	21.8	18.9
Longitudinal flange breadth (mm)	221.9	222.7	223.2	362.8	363.7	353.7
Transverse web thickness(mm)	6.2	7.2	7.5	5.1	5.0	7.8
Transverse web height (mm)	834.9	960.4	1000.3	610.4	604.9	1002.2
Transverse flange thickness (mm)	12.1	9.1	9.0	5.7	5.5	9.0
Transverse flange breadth (mm)	409.4	396.4	400.5	247.7	244.1	401.0

4. Results

The NSGA-II optimizer was executed for each of the five grillages studied. In general, this optimization problem was somewhat challenging for the optimizer to solve efficiently. Depending on the initial random number seed used the number of generations and individuals required to get a converged Pareto front varied. The results shown in this paper generally reflect the most dominant Pareto front from a number of runs of the optimizer. Table 8 gives a summary of the Pareto fronts created for the five different sized panels and the fronts are shown in Fig. 8. To allow for easier comparison across panel sizes the costs for each panel have been normalized by the area of the panel in Fig. 8. In each case, all 100 individuals used in the optimization were on the Pareto front by the final generation. In general, it is shown that, as the producibility score increases, the cost per square meter also increases proving that the introduced producibility metric is in competition with the traditional cost metric. This also indicates that additional information is being captured in the producibility metric beyond what is in traditional cost model; therefore designers need to be aware of potential tradeoffs between producibility and cost predictions.

The values of producibility scores for all five panels are approximately the same as are the costs per square meter. The fact that the normalized costs are similar is not surprising and supports the validity of the cost model. However, the fact that the values of the producibility scores stay relatively the same is surprising as intuitively the size of the panel should have an effect on how producible it is. While the individual producibility values are relatively similar, the sizes of ranges of the producibility scores do vary significantly. Further analysis of this trend will be presented in Section 5.

The individuals on the Pareto front for each panel size had the same amount of stiffeners in the longitudinal and transverse directions meaning all the variation in both cost and producibility was caused by different plate thicknesses, web heights, and flange breadths in each individual.

The producibility scores were driven by different elements for each sized plate tested. Typically the score increased as the height of the webs and breadth of the flanges increased. The base plate is typically thicker for the designs with higher producibility scores. Table 9 shows the properties of lowest cost, middle range, and highest producibility score for the 8 m × 16 m and the 5 m × 4 m panel cases. The trends seen in this table are also evident in the other three panel sizes. The ultimate strength constraint was active for most of the individual panels and was the main driver in the designs.

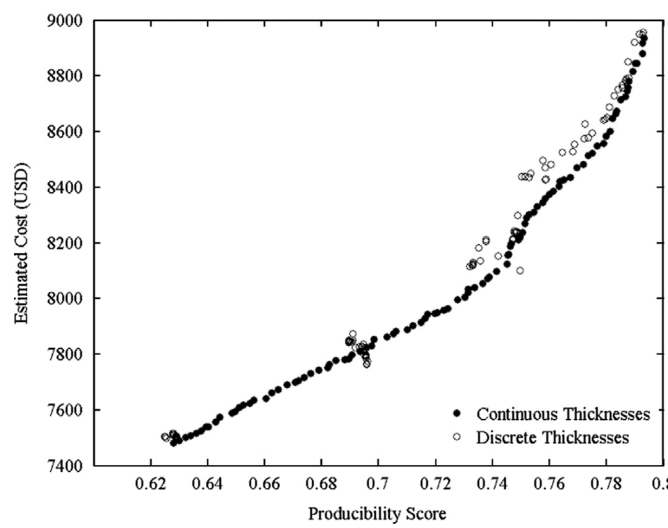


Fig. 9. Pareto fronts for discrete and continuous plate thicknesses for the 5 m × 4 m panel.

Continuous variables were used for the various plate thicknesses in this optimization to ensure smooth Pareto fronts but it is understood that steel plates come only in discrete sizes. Fig. 9 shows how the Pareto front changes for the 5 m × 4 m panel sizes when discrete plate thicknesses are used. Individuals on the Pareto fronts cluster based on the thickness of the base plate but the ranges of the producibility scores and estimated costs do not change.

5. Discussion

In addition to supporting the notion that the producibility metric is adding new information beyond what is available in the Rahman and Caldwell model, the Pareto fronts from the last section often indicate that substantial gains in producibility can often be made with minimal increases in cost, further suggesting that including an explicit producibility metric would be valuable for early-stage optimization. Conversely, this also indicates that formally optimizing for cost alone may require sacrificing significant producibility gains as the optimizer rigorously converges to the extreme left-hand end of the Pareto front. While it would be possible to convert the producibility metric to a cost measure if all details of a specific shipyard's production process were known, the shape of the Pareto front revealed here also supports the simpler notion that a designer can choose a reasonable design by looking for the “knee” in the Pareto front. Such simple heuristic approaches may prove useful in cases where the shipyard may not be known *a priori*, for example in the public sector preliminary design before a request for proposal or tender is issued.

The remainder of this section will be dedicated a further analysis of the producibility scores found for the 5 m × 4 m panel. This panel was chosen as it has the largest range of both cost and producibility scores on its Pareto front. For the ranges of the physical properties of this panel size refer to Table 9. A graphical representation of the producibility elements for this panel is presented in Fig. 10. All the utility function values were taken from individuals along the Pareto front in the final generation of the optimizer.

In the case of the 5 m × 4 m panel every individual had five longitudinal stiffeners and two transverse stiffeners, this leads to a small range of *x*-direction access and *y*-direction access scores. The remaining fluctuation was cased solely by the various flange breadths in each design. The lack of variation in number of stiffeners also led the effective aspect ratio score to be the same value for each individual.

The more interesting elements for this sized panel are the ones that are associated with material thicknesses. For example, the stiffener spacing to plate thickness ratio score has an extremely large range with 44 of the 100 individuals achieving the maximum score and 64 of the 100 individuals scored over 0.8 which is associated with a “good” ratio. The panels that scored higher in this metric all have base plate thicknesses higher than 6 mm. Additionally, the thickness ratio score has a large range which is also predicated on the changing sizes of the base plate.

These trends are continued in all the other tested panel sizes. The *x*-direction scores tend to be low with a small range while the *y*-direction access scores tend to be high but also with a small range. Each panel size had only one effective aspect ratio score for every individual as each panel size had only one combination of number of transverse and longitudinal stiffeners. Expanding the lower and upper bounds on stiffener spacing may increase this solution space and lead to more interesting interactions in the producibility domain, but this could also lead to non-realistic panel designs.

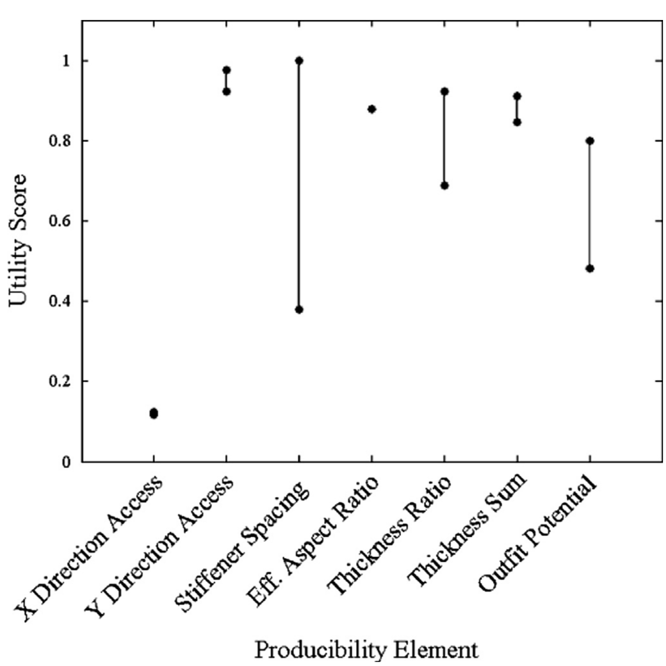


Fig. 10. Utility function ranges for 5 m × 4 m panels.

In all cases the ranges of the thickness sum scores are small which also means the ranges of welding costs for each panel size are small. Also, these scores were quite high which meant the combined thickness of the plates in the joints were typically near 25 mm which meant the welding costs in general were quite low. Welding costs tended to account for roughly 15–20% of the overall cost of each panel.

None of the individuals across any of the panel sizes managed to score a one on the outfit potential metric due to the interaction of the constraints. Because the height of the transverse stiffeners could not be reduced into the most desirable range the designs went to the other extreme to ensure there was ample height in the stiffeners to precut holes to run outfit through.

To account for different structural characteristics at different parts of the ship the required ultimate strength was varied for the 5 m × 4 m panel size (Fig. 12). Two additional scenarios requiring the panels to achieve an ultimate strength of 175 MPa and 225 MPa were run in addition to the original requirement of 200 MPa. Fig. 11 shows how the Pareto fronts changed as the ultimate strength constraint changed.

The Pareto fronts change as expected with the lower strength requirements producing less expensive panels with equal or better producibility scores to the stronger panels. Additionally, the lower the required strength the more spread out the Pareto front, suggesting that there is a larger solution space for those panels which is expected. Figure displays the individual producibility elements for these different optimization scenarios.

As expected, the lower strength panels generally have higher maximum utility values as well as larger ranges though it is interesting to note the *x*-direction access score is highest for the panel with the highest ultimate strength requirement. This is due to the very thick base plate found in the designs at this strength. This plate takes some of the load off of the longitudinal stiffeners, allowing the flanges on those stiffeners to be smaller thus increasing access space. It is also interesting to note that the 225 MPa and 175 MPa variations all have four longitudinal and one transverse stiffener instead of the five longitudinal and two transverse stiffeners found in the 200 MPa design.

The wide range of stiffener spacing to panel thickness scores for the 175 MPa panel is due to the large range of base plate thicknesses that could be used to meet the strength requirement. The panels that used the thinnest plates (approximately 5 mm) were the individuals that scored the lowest on this element. These panels would be at risk for both distortions while building them as well as while transporting or storing them before they were

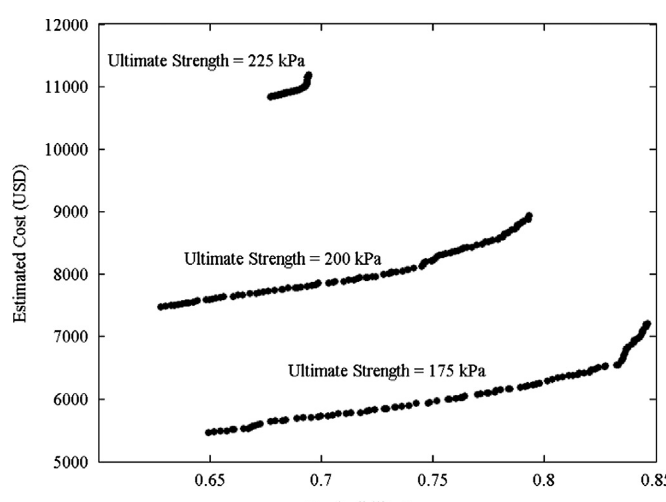


Fig. 11. Pareto fronts for different ultimate strengths of 5 m × 4 m panel.

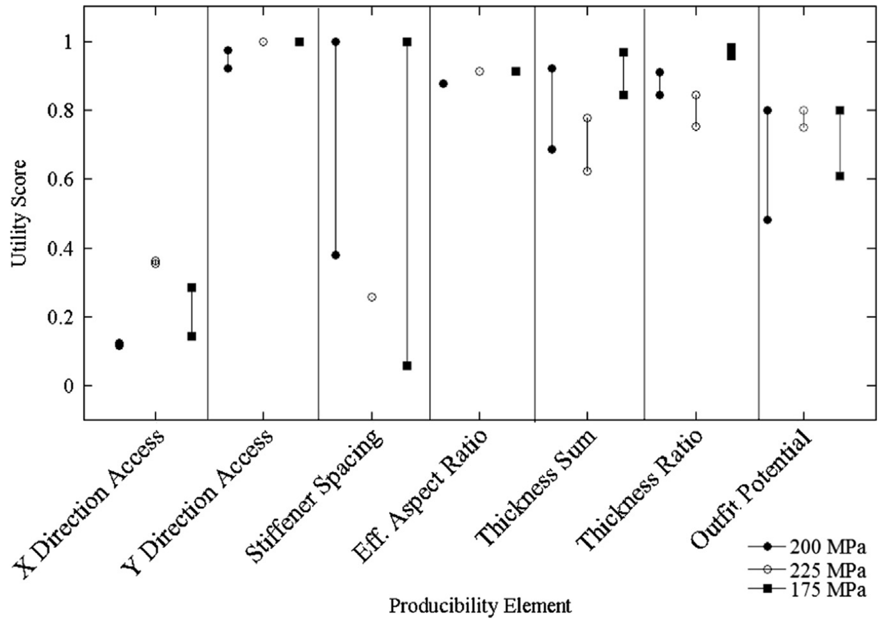


Fig. 12. Comparison of 5 m × 4 m panel utility function values for different ultimate strength requirements.

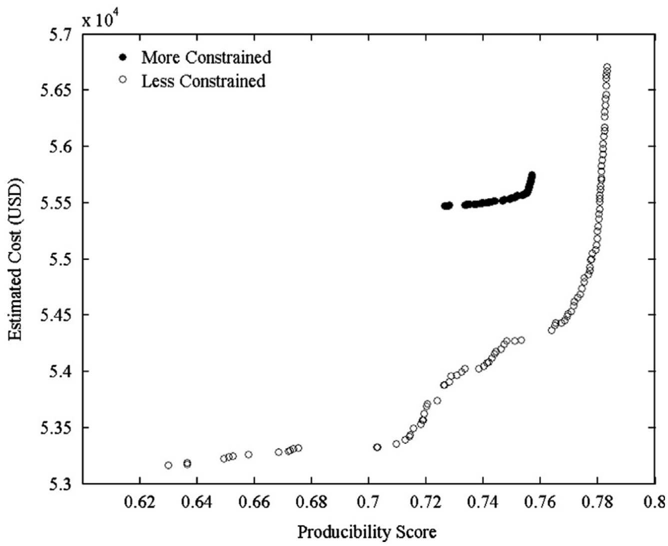


Fig. 13. Pareto fronts for 8 m × 16 m panel using different constraints.

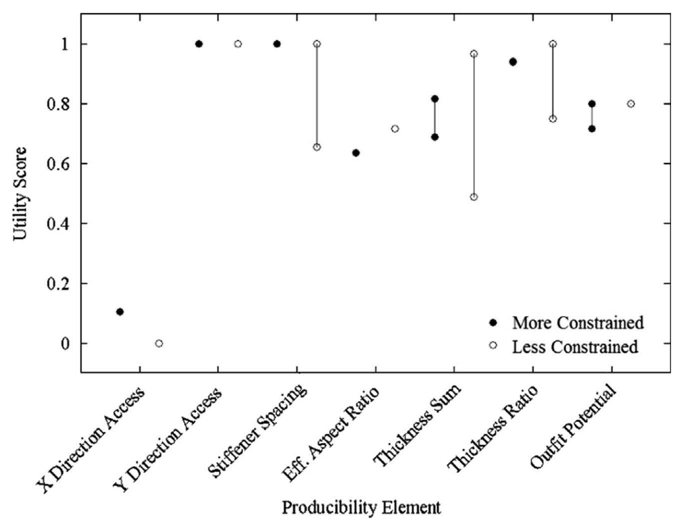


Fig. 14. Comparison of utility function scores for 8 m × 16 m panel using different constraints.

welded into the greater ship structure. Sometimes it can be advisable to take an increase in cost and weight for a panel to alleviate these issues. The 225 MPa panels scored very low in this category for the opposite reason. The base plates were very thick compared to the stiffener spacing and therefore would experience a considerable amount heat input from welding which could also lead to distortion or fatigue problems.

If the constraints not related to strength are removed or made less restrictive the resulting solutions also show a broadening of the solution space and an increase in permutations of the panel design. In Fig. 13 the original 8 m × 16 m panel is compared to one run without requiring the longitudinal flange breadth to be at least five times the longitudinal web height nor the transverse flange breadth to be at least two and half times the transverse web height. All other constraints and optimizer parameters were kept constant.

It can be seen that the Pareto front for the less constrained individuals has expanded appreciably while still maintaining the same shape as the more constrained Pareto front. In both of these cases there is a noticeable “knee in the curve” phenomenon where before this point large gains in producibility can be had for relatively small increases in cost. This shape is not as evident in all the smaller panels due to the smaller area to work with, though when run with the smaller constraint set the other sized panels do show the same broadening of the Pareto front. Fig. 14 compares the individual producibility elements of the more and less constrains 8 m × 16 m panel.

Upon analysis of the producibility elements it can again be seen that removing the constraints facilitated a much larger solution space. Interestingly, the less constrained designs saw a reduction in the *x*-direction access score even though they all 26 longitudinal stiffeners compared to the 32 longitudinal stiffeners for every design using the stricter constraints. This is because the longitudinal flanges were allowed to grow to such a size that the gap between them was minimal. Due to the wider stiffener spacing in the less constrained designs the range of the stiffener spacing to base plate thickness ratio score expanded but it did so in the less preferable direction. The thickness sum and thickness ratio scores were able to vary more as many more thicknesses of steels were used. The most producible and most expensive panels of the less constrained set were the ones that used the thinnest thickness flanges possible whilst making them have as much breadth as possible.

These analyses show that one producibility element is not the dominant driver throughout all scenarios, rather different panel sizes, strength requirements, and other constraints determine which producibility element is the key. This finding shows that the present method may be a valuable extension over standardized "rules of thumb" approaches such as those in Bunch (1993) which do not attempt to rank or prioritize different elements of producibility for different panel locations. For the original $5\text{ m} \times 4\text{ m}$ panel case achieving the best possible stiffener spacing to base plate thickness and outfit potential scores led to a more producible design whereas the producibility scores for the stronger panels were mostly dependent on the weld joint thickness ratios and sums. The lower strength panels had similar drivers to the original strength panels but were even more dependent on the stiffener spacing to base plate thickness utility score. For the more constrained of the $8\text{ m} \times 16\text{ m}$ panels the difference in producibility scores almost entirely on the joint thickness sum and outfit potential scores whereas the less constrained designs had large swings in the individual scores for stiffener thickness to base plate thickness, joint thickness sum, and joint thickness ratio elements.

6. Conclusions

In this paper, a new metric for producibility, taking into account welding access, welding difficulty (both time required and possibly of distortion) and outfitting difficulty, has been proposed. This metric represents an approach to distill existing studies in producibility into a simple formula that can be applied at the earliest stages in the structural design process when 3-D product models and detailed outfitting information is not yet available. This metric was compared with a traditional costing function presented by Rahman and Caldwell by means of a multi-objective optimization of a stiffened panel. The optimization showed clear Pareto fronts for five different sized panels which showed a traditional structural cost estimating model was in competition with the introduced producibility metric. By ignoring the producibility, a significant cost driver of a complete design is not taken into account, meaning a design that has the least material and the fewest welds may not be the least cost design in the long run. As producibility can be considered a cost driver, it would be possible to convert this metric into a dollar amount and combine it with an existing cost method to perform a single objective optimization to find the lowest overall cost panel. However, such an approach would require further research to convert the utility functions used herein into time and material costs associated with a given shipyard production scheme. Alternatively, multi-objective optimization, as used here, could be applied to located regions where large gains in producibility can be made with little impact on cost, and new designs located at the "knee" of the resulting Pareto fronts ensuring all easily-achieved producibility gains are incorporated.

Five different sized panels showed roughly the same values of producibility scores which differing costs corresponding to the various sizes. While the values of producibility scores were similar, the underlying utility function values producing these scores were different and were heavily dependent on the properties of the panels and the constraints the panels were required to meet. This difference indicates that applying a piecewise metric such as the one proposed here, which is able to model the actual panels, will be more successful than relying on general "rules of thumb" to include producibility concerns in early grillage design

The producibility metric could be expanded for use in a 3-Dimensional box structure, taking into account attributes such as overhead height in regards to shipyard worker mobility. Additionally, individual piece weights or plate sizes could be included to represent the ease or difficulty of a worker moving and positioning a piece of the structure prior to welding. Additionally, the difficulty of producing the base plate could be taken into account. Lastly, if this metric was expanded to score an entire ship, unit location (double bottom, cargo hold, superstructure, etc.) and outfit density (piping, electrical, HVAC, etc.), among other attributes, could be included. Regardless of what metrics are used to calculate it, producibility has a significant impact on the cost of a ship and it can significantly affect structural optimization and should be taken into account in all structural designs.

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