CONSIDERATION OF DESIGN FOR PRODUCTION PRINCIPLES IN SHIP HULL DESIGN

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Introduction

Traditionally, hull lines are developed by specialized hydrodynamicists (with little or no shipyard engineering and production experience) optimising the hull with respect to resistance and propulsion characteristics. But ship hull form design should consider hydrodynamic and producibility aspects and find a acceptable compromise. Hydrodynamic aspects, especially minimization of power requirements, lead to rather streamlined hull shapes that are relatively expensive to produce. Designers should incorporate production aspects that reduce work content significantly with small, if any, adverse impact on hydrodynamic and propulsion efficiency. This is possible as examples in the literature show.

A basic knowledge of the production processes is essential to discuss design for production (DFP), Parsons et al. (1999). The cost of producing stiffened hull panels is related to the curvature of the hull surface and that curvature's orientation relative to the principal stiffeners of the surface. The amount of curvature determines whether the plate will be rolled, pressed, flame bent, etc. The orientation of curvature relative to the principal frames (transverse or longitudinal) determines whether or not the frames may have to be curved as well. The construction of steel ships involves a large number of steel plates which form the hull surface panels. These plates and shapes require usually special shaping, unless they are in a region of the ship where the hull is flat, as e.g. in parts of the bottom or side plating in the parallel midbody of the hull. Plates that need to be shaped in only one direction (single curvature) or with only a slight amount of backset can be formed using rolls. These large machines typically consist of a large diameter top roll and two small diameter bottom rolls. Plates with complex (reverse) curvature or large curvature in both directions (double curvature) are fabricated using large hydraulic presses. Presses are also used if the fabricated material's strength, thickness, and/or length exceed the capacity of the rolling machine. Pressing is also used in conjunction with rolls to produce curved stiffeners. Depending on the shipyard fabrication facilities, the types of presses used and the ways in which they are used may vary. A standard line press may be used for moderate double curvature and a ring press may be used for severe double and reverse curvature. Often the required shape exceeds the capacity of cold forming techniques. In these cases, thermal forming (line heating) techniques can be used alone or in conjunction with cold forming to produce the desired curvature while keeping residual stresses in the material at an acceptable level. Even in full form hulls the work content in forming the curved shell plates and fitting them to the internal structure is a significant portion of the total structural man-hours, because plate forming is still largely a manual process requiring high skill. It is not a repeatable process and suffers from inaccuracy.

The local curvature of the hull determines to a large extent the production process needed and thus the cost of producing a particular hull segment. Some concepts of hull design for producibility thus follows directly from an analysis of hull curvature properties. The metal used for the construction of thin curved shell structures such as ships (but also automobiles and aircraft) is originally produced as thin, flat sheets (plates). The formation of curved structures from flat sheet material inevitably involves some degree of plastic deformation of the material of the plate. There is a special class of surfaces, known as 'developable' surfaces, which can be readily fabricated from sheet material because they require only bending of the sheet, rather than any degree of stretching, shrinking, or other in-plane deformation. Developable surfaces are much easier to produce and consequently highly preferred in design for production, Letcher et al. (1988), Letcher (1993). A number of small ships have been designed with completely developable hull surfaces. The Gaussian curvature K is defined as the product of the two principal curvatures: $K > 0$ convex or concave surface, $K = 0$ developable surface, $K < 0$ saddle-shaped surface (reverse curvature). Developable surfaces are ruled surfaces, where all points of the same generator line share a common tangent plane: plane (trivial case), conical, cylindrical or tangent surfaces of a curve, or a composition of these types. Kilgore (1967) developed an often referenced graphical method to determine developable surfaces between two curves in space. Rational Bezier or B-Splines can be used to produce developable curves, e.g. Bodduluri and Ravani (1992,1993). Nolan (1971) presents a computer-aided method to determine developable surfaces following in principle Kilgore's approach, but using Theilheimer splines to automate the process. Clements (1981,1984) presents a computer method to develop arbitrary developable surfaces for patches on ships (in his application planing hulls). The corresponding software is commercially available, www.dal.ca/~nutech/techs/ttc40.html. Konesky (1994,2001ab) improved the algorithm of Nolan, which does not always find a solution. The resulting software is available as AutoDevSurf. Also the Fairway program, www.sarc.nl, is based on the Nolan/Clement theory with some modifications for the ship ends. Odense Steel Shipyard cooperated with TU Wien to develop a method to approximate a given surface by a developable surface, Chen et al. (1998). Söding (1973) describes a method for the development of doubly-curved plates for German shipyards. In practice, a small amount of double curvature (twist) is acceptable, but literature does not quantify what is 'small'.

Historical review of simplified hull forms

Bertram (1998), Bertram and El Moctar (2002) give more extensive historical literature reviews of design for production for ship hulls, which is reproduced in part by Lamb (2003). Therefore it suffices to give here just a short review. Research into the 1960s focused on simplified hull shapes introducing usually one or several knuckle lines. Occasional claims of hydrodynamic performance equivalent to that of faired hulls appear exaggerated, but Johnson (1964) showed in model tests that moderate hull simplifications may actually improve hydrodynamic performance, while larger simplification lead to unacceptable hydrodynamic penalties. The Pioneer form of Blohm & Voss featured only flat plates on the hull except for the regions on the ship ends, Fig.1, Gallin (1977). The concept has already many modern ideas of design for production: reduction of different parts to exploit economies of scale for the single parts, modular approach to offer family of ships (later successfully implemented in the Meko frigate system of Blohm&Voss). This introduced a multitude of knuckles. Contrary to the expectation of the designers, this resulted in a more difficult assembly process due to fitting problems. Fatigue strength problems appeared after some years of operation in these ships. Kiss (1972) concluded that the savings in hull construction would not be able to offset the cost for fuel and power plant increases. However, there were many good ideas in the Pioneer ship like modular design of a family of ships, later successfully implemented in the Blohm &Voss MeKo programme.

From 1975 to 1995, IHC-Holland produced a fairly large number of hopper dredgers, with all shell plates developable, Fig.2. Those vessels ranged from 60 to 120 m in length. Hydrodynamic studies in the 1970s showed that - with properly chosen chines - the resistance increase of a developable surface was only marginal, compared with a doubly-curved surface. The yard even experimented with straight stiffeners on the shell plate in the direction of the rulings, instead of vertical frames. However, it appeared that the savings on the lack of bending of the stiffener were lost by a more complex end-connection of the stiffeners. After the year 2000, 'fashion' changed and today they build in majority vessels with doubly curved plates. The exact reason is unknown. (personal communication of Herbert Koelman (SARC)).

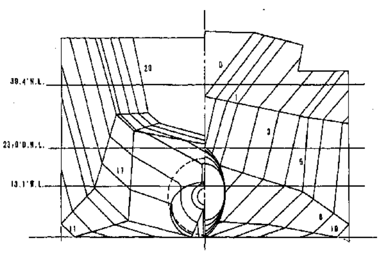

Fig.1- Pioneer ship

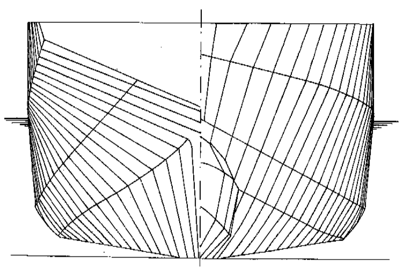

Fig.2- IHC dredger hull

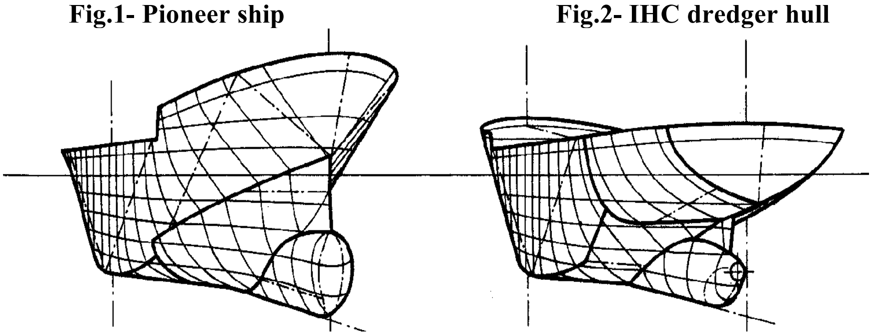

Fig.3- Ship hull composed only of developable surfaces; source: Schenzle, HSVA

Schenzle's DFP hull, Fig.3, form consists almost exclusively of single-curvature and flat plates. This hull features bulbous bow and stern bulb and shows that design for production hulls are feasible without sacrificing hydrodynamics.

Several designs with developable surfaces have been developed for smaller ships which form a particular interesting market. They are usually built in series, so the ratio of production cost to development cost is higher than for big one-of-a-kind ships. Also bigger ships have naturally more flat plates and developable surfaces than smaller ships.

General principles in ship hull design for production

Global DFP aspects concern the main dimensions, Schneekluth and Bertram (1998):

- Maximize flat of bottom and flat of side.
- A small L:B reduces the number of frames and reduces the hull steel weight.
- A long parallel midbody increases the amount of flat plates and reduces the number of different frame shapes. The number of repeated parts and sections is increased.
- An large block coefficient increases the amount of flat plates.
- Select a bilge radius so that one plate width can handle the bilge strake. A small bilge radius reduces the amount of bending for frames and plates. The bilge radius should be selected so that the side block erection joint is above the tangent of the ship's side to the bilge radius, and above the tank top.

Local aspects (small changes in the hull) can also improve the producibility of a ship. The surfaces of modern hull geometries feature over wide areas a very small value for the smaller of the two principal curvatures. That is, the surface is almost developable and most plates can be cold formed. Only small changes in the hull form may be required to give developable hulls. Especially the intermediate areas between flat regions in bottom and sides to the ship ends can benefit from such slight modifications which may have only negligible effects on the power requirements. The following list is taken largely from Kaine and Ingvason (1990):

- Avoid excessive curvature in surfaces on the hull. All available shipbuilding CAD/CAM systems have fairing programs that include tools that show the extent of curvature. These can ensure that the designed hull form only contains surfaces with curvature within the manufacturing and economic capability of a given shipyard.
- Avoid double-curvature surfaces in hull plating. Many of the hull lines can be straight in one direction without loss of hydrodynamic performance or appearance. A double-curvature plate will usually require heat treatment and increased work input to achieve the required shape. Single-curvature plates lead also to less scrap. In any case, curvatures of plates should be kept small enough to avoid castings as these make the structural detail three to four times more expensive.
- Avoid shapes that require castings in stem and stern.
- Straight sections and single-curvature plates improve welding productivity (more automatic welding), eliminate bending, and reduce the number of different parts (more repetition of

frames) to be manufactured, tracked, assembled and installed.

- Keep the inner structure straight. Even though the hull lines are curved, there is no need to bring the exterior hull shape into the interior hull structure. The internal structure then serves as a transition between the curves of the hull exterior and the straight lines and flat surfaces of the interior.
- Knuckles necessary to achieve a less complicated curvature should be located at unit breaks. Do not place knuckles either at or between bulkheads and decks, but 20cm to 30cm from the bulkheads or decks where the breaks will be made. Knuckles above the waterline do not influence the hydrodynamic performance! However, the fatigue strength of the knuckles should be investigated. A large number of knuckles may lead to problems in fitting during assembly and in fatigue strength. This may more than compensate the advantages of reducing curvature of parts.
- Establish unit breaks early in the design process and locate them for repetitive design and construction of the units. The location of the unit breaks can be critical to cost reduction. For some ships, such as tankers and bulk carriers, much of the structure is repetitive. By careful location of the unit breaks, the units to be fabricated can be built from one set of plans with resultant savings in engineering and production man-hours. This not only allows for assembly-line type construction with the cost benefits of line production, but also reduces the man-hours required to design the ship. The early location of unit breaks provides another benefit by permitting the designer to locate the various items of machinery and equipment in positions which facilitate unit outfitting. Any equipment which happens to be located across a break cannot be installed until after the units have been erected which makes it more costly. Joining the shell of two units is easier if the joint in one direction is stiff (near a rigid transverse structure) and the other is flexible (distant from rigid transverse structure).
- Midship cross sections with rise of floor for displacement ships are outdated. Modern ships are designed with large flat bottoms. The shipyard maximum plate width should be used as the flat keel width.
- Curved stems may look nice, but are costly. Even slight departures from a straight-line stem will add to the difficulty in fabricating it. The simplest stem geometry is formed from cone segments. This will give elliptical waterline endings, not circular, as many designers' use.
- Bulbous bows are never easy or cheap to build and the overall design follows purely hydrodynamic considerations. However, bulbs can be constructed from (nearly) developable patches, and adding bulbs with appropriately located knuckles lines between bulb and forebody usually improves producibility.
- The term 'stern' usually covers two important independent but obviously connected items, namely the propeller aperture and the rudder arrangement, and that portion which is mostly above the design waterline aft of the rudder stock centreline. The upper stern development proceeded from the counter stern to the cruiser and then transom. Merchant ship

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designers adopted the transom stern because of its obvious economy, but also as it maintained deck width aft which was important in deck cargo ships, such as container ships and ships with aft deckhouses. Transom sterns should be designed as vertical flat plate.

- The aftbodies of single-screw ships often feature regions with reverse curvature. This reverse curvature can be eliminated by carefully locating plate seams and butts at the transfer lines from convex double curvature plates to concave plates. However, the work content is still significant. There are two options in this case, Lamb (2003):

  1. Follow the normal single-screw hull form as closely as possible by incorporating one or more chines, joined by straight lines or simple sections. The chines should lie in flow lines to prevent cross flows as much as possible.
  2. Design the aftbody as pram-type with a skeg added. This approach has the least work content.

Understanding the qualitative levers to increase producibility is an important step for the design engineer. The next step is to quantify the production cost. Approaches in this direction are discussed in the next chapter.

Evaluating producibility of hull forms

Estimating the production cost is a fundamental part of ship design. The option for estimating the production cost differ in the required information for the input data. The less information is needed, the earlier a method can be employed in the design process. The more information is used, the finer differences between design alternatives can be analysed. The methods for estimating production cost are classified into top-down (macro, cost-down or historical) approaches and bottom-up (micro, cost-up or engineering analysis) approaches.

The top-down approach determines the production cost from global parameters such as the weight of the hull, the block coefficient, the ship length etc., Schneekluth and Bertram (1998). The relations between cost and global parameters are found by evaluation of previous ships. Thus, the top-down approach is only applicable if the new design is similar to these previous ships. Also, the cost estimation factors in the approach reflect past practices and experience. Despite its popularity and frequent references in the literature, top-down approaches have serious disadvantages which are often overlooked or concealed:

- The approach uses only global information and is thus incapable of reflecting local form changes or details of the design improving producibility.
- The approach is based on weight. Any change which increases weight will automatically increase the cost estimate regardless of the real effect on cost. Extreme light-weight designs may drastically increase the number of required hours, while large frame spacing may increase weight, but decrease necessary man-hours. This is not reflected in the formulae!

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- The approach is based on historical data, i.e. historical designs and historical production methods. In view of the sometimes revolutionary changes in production technology over the last decade, the data and formulae may sometimes be called 'prehistoric'. They do not reflect new approaches in structural design or production technology.
- The approaches were probably based on inaccurate data even at the time they were derived. Shipyards are traditionally poor sources of cost information. The data are frequently skewed reflecting pressures of the first-line managers and other factors.

The alternative bottom-up approach breaks down the project into elements of work and builds up a cost estimate in a detailed engineering analysis. This approach also uses cost factors, but they are based on work studies of 'atomic' elements of the operation, such as man-hours per weld length using a certain welding technique and position. These elementary actions are supposed to be independent of application. In reality, they may well differ between different welders (experience, work ethics), days (workload, climate), etc. They are then to be determined and interpreted as a statistical average.

Table I shows a simple example of a possible bottom-up calculation of labour cost and material cost for hull production. For each work process the number of necessary man-hours is computed. This is done by multiplying the average man-hours per unit with the number of units for this work process. Units for a work process could be: 'number of frames and plates requiring bending', 'meters of weld' etc. The total number on necessary man-hours is then the sum of all man-hours for the individual work processes. The man-hours are converted into cost by multiplication of the man-hours for each work process with the shipyard specific cost factor (monetary unit/man-hour) for this work process. Again the sum of all work processes give the total labour cost. Similarly the material cost are estimated. The depth of differentiation of the individual work processes is chosen appropriately.

The bottom-up approach requires more effort and detailed information than the top-down approach, but unlike the top-down approach, the bottom-up approach captures also differences in design details. Changing the local hull geometry has e.g. an influence on the number of frames which require bending, the effort in plate bending and the degree of weld automation which depends on the curvature of the weld joints. All these effects are reflected by an appropriate decomposition of the total work process into its individual components. The most advanced application in this field employing formal optimisation and bottom-up approach is the work of Rigo for ship structures using his LBR-5 system, Rigo (2001a,b,2003a,b), Rigo and Fleury (2001), Karr et al. (2002). This is probably the only such system which has been applied in shipyard application.
Rather than employing formal optimisation with associated sophisticated models, calculations in practice will more often be based on simple spreadsheets as shown in Table I. These spreadsheets can quickly be modified for new ship design projects and feedback from production can quickly be incorporated. The bottom-up approach described in Table I requires a significant amount of detailed

information about the product and how it can or will be constructed. The major advantage of that technique is that it specifically considers the actual work content of the product and provides a realistic cost estimate for the construction effort. At present, this approach is not available in most shipyards; neither are historical databases from which it could be developed. It is then necessary to develop an appropriate approach, and collect the data required.

Until such an approach is fully developed for all processes, a less precise but similar approach could be used by applying known data and ‘guesstimates’ to the various design and production factors for each design alternative. The calculation is then programmed and interfaced to structural design CAD systems, as shown by Sasaki (2003) for Mitsubishi Heavy Industries. The cost estimation function in the CAPP (computer aided process planning) system of Mitsubishi multiplies weld length by posture by a factor reflecting the work difficulty (e.g. 1 for downward, 2 for upward, 1.5 for horizontal):

$$C_{production} = \Sigma\,(W_{conversion} \times C_{unitconst})$$
$$W_{conversion} = W_{real} \times K$$

$C_{production}$ is the cost for production of one block, $W_{conversion}$ converted welding length (considering the different difficulty of welding depending on posture), $C_{unitconst}$ the cost to weld 1m for each posture, W_{real} the actual welding length, and K a coefficient to express the difficulty of the welding work. The system allows thus to compare different structural designs or construction methods.

For the selection of the best of a number of alternatives (optimisation), a relative comparison is sufficient and easier to perform. Also, the comparison can be limited to those regions where design alternatives differ. Wilkins et al. (1993) describe such a technique. Although this alternative method provides only a relative comparison of various design alternatives, as opposed to the absolute quantitative evaluation described above, it may be accomplished when less data are available. This relative evaluation method is based on the 'Analytic Hierarchy Process' (AHP) of Saaty (1980).

"The first step involves breaking down the situation to be evaluated into those criteria which affect the process under evaluation. Each of these criteria are further broken down into the sub-criteria which affect them. This process continues until the most basic elements which control the criteria are identified. In this way, the hierarchic order of all of the significant variables are determined. In the next step, the relative weight to be given to each of the variables is determined. This is accomplished by pairwise comparisons of related criteria [...]. In accomplishing this step, the intuitive knowledge of experienced individuals is taken into account, as well as specific information available."

In doing each pairwise comparison, a scale of 1 to 9 is used, where a 1 means both parameters are equally important and a 9 means that the corresponding parameter is much more important than (actually, 9 times as important as) the other. This relative comparison of the importance of the criteria is converted into weighing factors for the individual parameters such that the sum of all weighing factors is 1 (or 100%). While this process may appear tedious, it has to be performed only once for a specific ship project and design phase. Once the criteria to be evaluated have been determined and their weighting values calculated, they are used for evaluating each set of design alternatives. Again, we use a scale of 1 to 9, only this time for the relative merit. For each criterion, the worse alternative gets the value 1, the better alternative a value of 1 to 9 indicating the degree of improvement in producibility. When hard data (e.g. weld lengths) are available, they can be entered directly, taking care to enter the data such that the preferred alternative receives the higher value and values are appropriately normalized. The evaluation factors are then multiplied by the weighting factors and summed to a total. The alternative which is easier - thus cheaper - to produce will have the higher number in total evaluation. Table II illustrate the process of relative evaluation for two alternatives. The criteria listed in Table II are one possible set of criteria deemed appropriate to evaluate the producibility of hull designs.

The possibility to combine hard, quantifiable data with soft, relative evaluation of qualitative aspects is a big advantage of the relative comparison. This approach is still capable of capturing design details, but the relative comparison can of course only determine which alternative is easier to produce. It cannot directly quantify the difference in production cost.

Ross (1995,2004), Ross et al. (2001), Ross and Hazen (2002) proposed a simple cost estimate method implemented in a user-friendly module which allows cost estimates at various levels of design with associated levels of confidence and detail of input. The method appears to combine exact data (e.g. for certain equipment) with regression analysis of past cost statistics for certain ship types.

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Table I: Bottom-up approach for estimating production cost

work process	man-h/unit	units	man-h	Euro/man-h	Euro
bending frames					
bending plates (single curv.)					
bending plates (double curv.)					
manual welding					
automatic welding					
TOTAL (labor)					
Material			**units**	**Euro/unit**	**Euro**
Frames					
Plates					
welding material					
TOTAL (material)					
TOTAL (lab.+mat.)					

Table II: Cost estimating form

	Relative	merit (1...9)	evaluation	Relative	value
	alternative A	alternative B	Factor (0...100%)	alternative A	alternative B
number of frames					
frame curvature					
number of plates					
plate curvature					
weld length					
degree of weld automation					
TOTAL			1.00		

Relative cost estimate based on expert opinion

Parsons et al. (1999) describe a similar approach to estimate production cost of hulls suitable for relative comparisons. This approach attempts to quantify the relative improvement between alternatives. Eight types of plates (from flat, no fabrication to high reverse double curvature) were evaluated with relative cost factors following expert opinion (of Prof. Thomas Lamb, Univ. of Michigan). The classification requires only the evaluation of a non-dimensional backset ratio which is relatively easy to determine in CAD systems. The backset is defined as the rise of the plate above a flat plane divided by the length of the plate. The longitudinal backset ratio is denoted as b = A(+)/L where (+) implies that the plate is bent downward; the transverse backset ratio is defined correspondingly along the transverse direction. Then the plate curvature can be is expressed in terms of b_1, the backset ratio in the largest principal curvature direction, and b_2, the backset ratio in the orthogonal direction.

Parsons et al. (1999) derive then a scalar metric (value) for the hull producibility by integrating the local cost as function of the local curvature over the hull. The local curvature is given easily by common CAD systems. The actual hull production will involve the formation of a finite number of plates of standard sizes for a particular shipyard. However, Parsons et al. assume that the aggregate or integral of the local or differential area curvature information will effectively represent the overall cost of hull plate forming. This simplifies the problem. In reality, choosing appropriate plate sections can reduce considerably the production work for the hull shell plating. However, the single, easy to compute metric for producibility is valuable for early design and educational purposes. The metric can be included quickly in design systems stimulating students to appreciate the producibility implications of their hull form design choices.

An approach for a quantitative trade-off of ship hull form

Kaeding and Bertram (1998), Bertram (1998) present a simplified approach for a trade-off between ship hull production aspects and hydrodynamic aspects, applying the method to a Series-60 hull, i.e. a simple and outdated hull geometry. For a quantitative trade-off between production cost and operational cost, only the cost differences between alternatives need to be computed. Table III shows as the spreadsheet used to determine absolute difference cost between two alternatives.

Table III: Estimate of production cost

			Alternative A			Alternative B		
work process	**Man-h/unit**	**Euro/man-h**	**units**	**man-h**	**Euro**	**units**	**man-h**	**Euro**
bending frames								
bending plates (single curv.)								
bending plates (double curv.)								
	man-h/m	**Euro/man-h**	**meter**	**man-h**	**Euro**	**meter**	**man-h**	**Euro**
manual welding								
automatic welding								
TOTAL (labour)								
material		**cost [Euro/t]**	**mass[t]**		**Euro**	**mass[t]**		**Euro**
Frames								
Plates								
welding material								
TOTAL (material)								
TOTAL (lab.+mat.)								
difference cost to altern. A								

Table IV: Relative cost estimate

Criterion			rel. merit		eval.	rel. eval.	
	altern. A	altern. B	altern. A	altern. B	factor	altern. A	altern. B
	a	b	c	d	e	f=c*e	g=d*e
number of plates							
- flat			b/(a+b)	a/(a+b)	0.24243		
- single-curv.			b/(a+b)	a/(a+b)	0.08532		
- total			a/(a+b)	b/(a+b)	0.56444		
weld meter							
- automated			b/(a+b)	a/(a+b)	0.07859		
- total			a/(a+b)	b/(a+b)	0.02922		
TOTAL					**1.00000**		

The absolute estimate of production difference cost requires the knowledge of the quantity 'man-hours/unit' for the individual units. This is not available to academia and often also not available to shipyards unless an appropriate management information system monitors these values. Therefore Kaeding used instead the relative cost estimate. Wilkens et al. (1993) give criteria for the evaluation of ship design alternatives and necessary factors. These factors need typically be determined for individually structures and shipyards. So an extension to real-life applications may again involve monitoring and coefficient fitting to case histories. Selecting only those criteria with relevance to hull design Kaeding derives Table IV.

There is no criterion to evaluate directly the curvature of frames. But as plate curvature and frame curvature are related, the consideration of plate curvature implicitly leads to a consideration also of frame curvature in evaluating producibility. The number of frames will be kept constant when just considering local hull form alternatives. But the number of plates can vary if in one alternative the curvature is such that only smaller plates can be processed.
Only the columns 'alternative A' and 'alternative B' under 'input' in Table IV are to be supplied by the user. Here the direct hard data for number of plates and weld length are directly filled in. This version of a spreadsheet evaluates the production cost, i.e. the better alternative will feature a lower relative evaluation corresponding to lower production cost. This is considered in the choice of the 'relative merit' factor. E.g., an alternative with fewer flat plates - thus implicitly more plates requiring complicated bending - will have a higher factor for 'relative merit'. (Similarly, it would be possible to set up a spreadsheet that evaluates as 'merit' the producibility and not the building cost, i.e. invert the merit. Then the 'merit factors' would have to be switched between columns A and B.) Note that the 'merit factors' are non-dimensional and normalized. This is necessary to ensure comparability of various scales and units in the original criteria.

The application used a manual plate arrangement on the ship hull. An ‘integral’ evaluation of curvature over the hull may be used when the hull shape is determined in the CAD system. Such an approach based on the ‘magic coefficients’ of Parsons et al. (1999) has been implemented in the ship design system used at the University of Michigan (to raise students’ awareness of production aspects in early design; as the hull shape is modified, an indicator on the screen shows whether producibility goes up or down) and within the FANTASTIC research project (optimisation of ship hulls with a simple producibility criteria).

In the academic case study of Kaeding, moderate simplifications showed no increased resistance at design speed in CFD (computational fluid dynamics) analyses. (The wave resistance was slightly increased, the frictional resistance slightly decreased.) The production cost for the hull and stiffeners alone was estimated to be approximately 20% less for the alternative with straightened sections.

Conclusion

Attempts to introduce simplified hulls in ship design have a long history. A careful balance has to be found between production aspects and operational aspects. 'Design for Producibility' alone is a too narrow approach for ship design. But in a 'Design for X', where X stands for a variety of design goals, producibility will play a major role. Extreme simplification has never been successful in the history of ship designs, but many ship design until today could benefit from moderate simplifications. It is important that designers realize that the 'optimum' hull changes with time, especially as new production technologies are introduced. Simple estimates may help in coming close to an optimum, but these estimates require monitoring production cost within a shipyard. However, no European shipyard has at present the necessary detailed data from monitoring production processes. Detailed monitoring as in some Japanese shipyards - perhaps embedded in a research projects - could change this situation. A final note: While saving potential in designing the hull may not be ignored, the largest potential for cost reduction by increased producibility lies inside the ship.

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