WORK STATION INFORMATION SHEET

WORK STATION NO.: S5

PRODUCT CODE: M 417

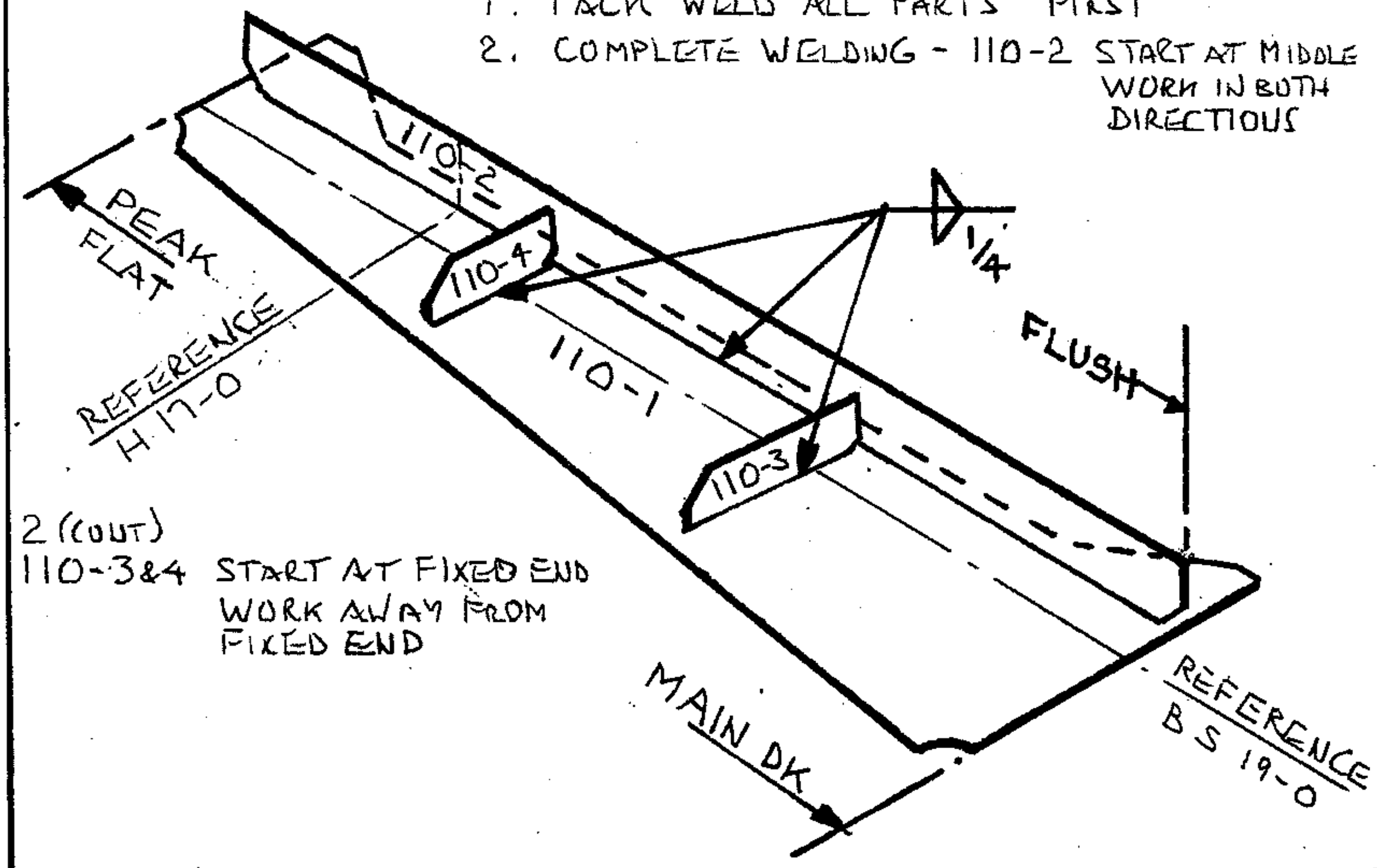
JOB: 000

PRODUCT NAME: SUB-ASSEMBLY

NUMBER OF PRODUCTS: 1 (ONE)

PART CODE	PART NUMBER	DESCRIPTION	QUANTITY PER PRODUCT	QUANTITY ALL PROD.
1000421600	110-1	0.375" PLATE	1	1
1100440200	110-2	6" x ½" FLAT BAR	1	1
1100130101	110-3	4" x ¼" FLAT BAR	1	1
1100130101	110-4	4" x ¼" FLAT BAR	1	1

1. TACK WELD ALL PARTS FIRST
2. COMPLETE WELDING - 110-2 START AT MIDDLE WORK IN BOTH DIRECTIONS



2 (CONT)
110-3&4 START AT FIXED END WORK AWAY FROM FIXED END

PREP. BY: T

DATE: 5-24-85

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Figure 14.8 Structural Subassembly Workstation Information

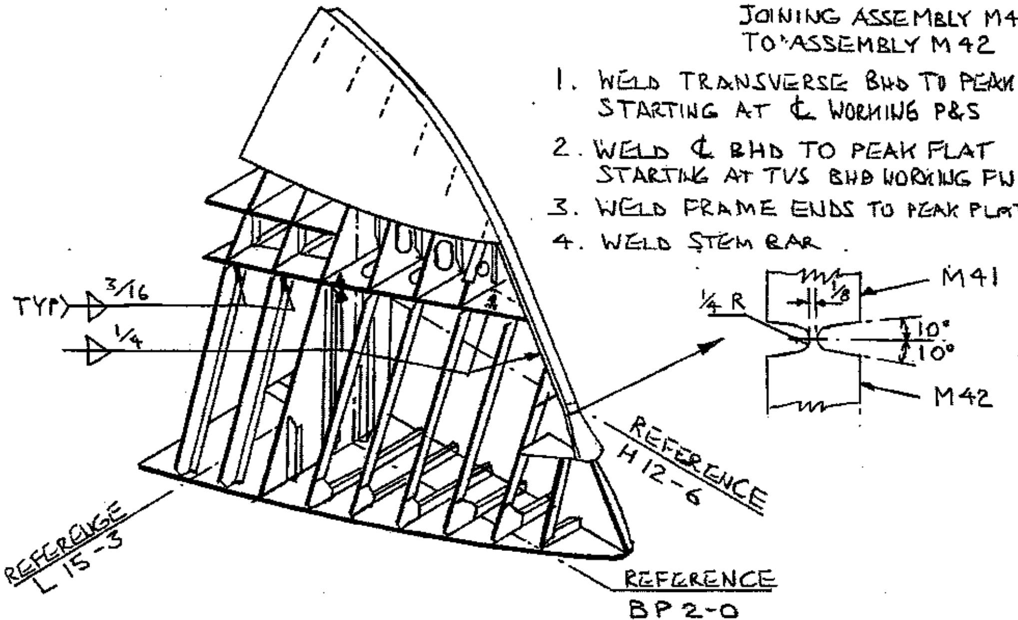
WORK STATION/ZONE INFORMATION SKETCH

WORK STATION NO.: S 21	PRODUCT CODE: M 4	JOB: 000
PRODUCT NAME: MODULE - LOWER BOW		NUMBER OF PRODUCTS: 1

SEQUENCE 12

JOINING ASSEMBLY M41 TO ASSEMBLY M42

1. WELD TRANSVERSE BHD TO PEAK FLAT STARTING AT ℄ WORKING P&S
2. WELD ℄ BHD TO PEAK FLAT STARTING AT TVS BHD WORKING FWD
3. WELD FRAME ENDS TO PEAK FLAT
4. WELD STEM BAR



PREPARED BY: T	DATE: 5/24/85	PAGE 14 OF 17

Figure 14.9 Structural Block Workstation Iinformation

WORK STATION/ZONE INFORMATION SKETCH

WORK STATION NO.: 34	PRODUCT CODE: 321-300	JOB: 000
PRODUCT NAME: OUTFITTED UNIT - ELECTRIC		NUMBER OF PRODUCTS: 1 (ONE)

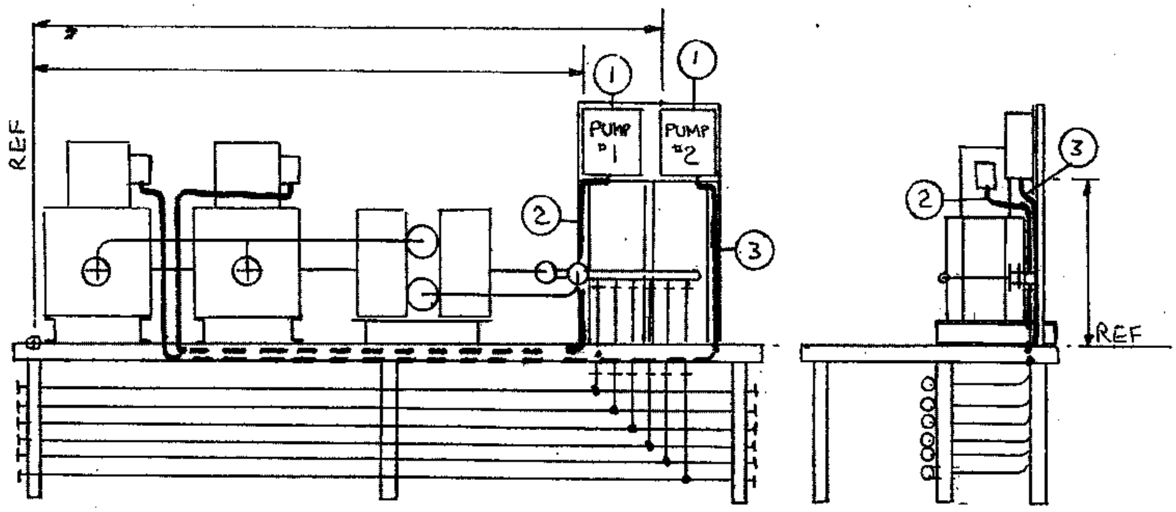


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Figure 14.10 *On-board* Advanced Outfitting Unit Installation Workstation Information

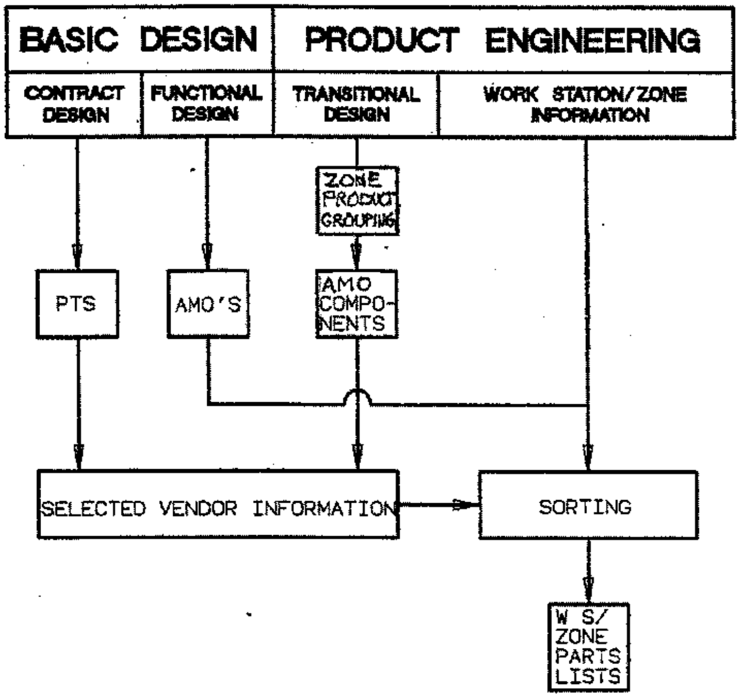
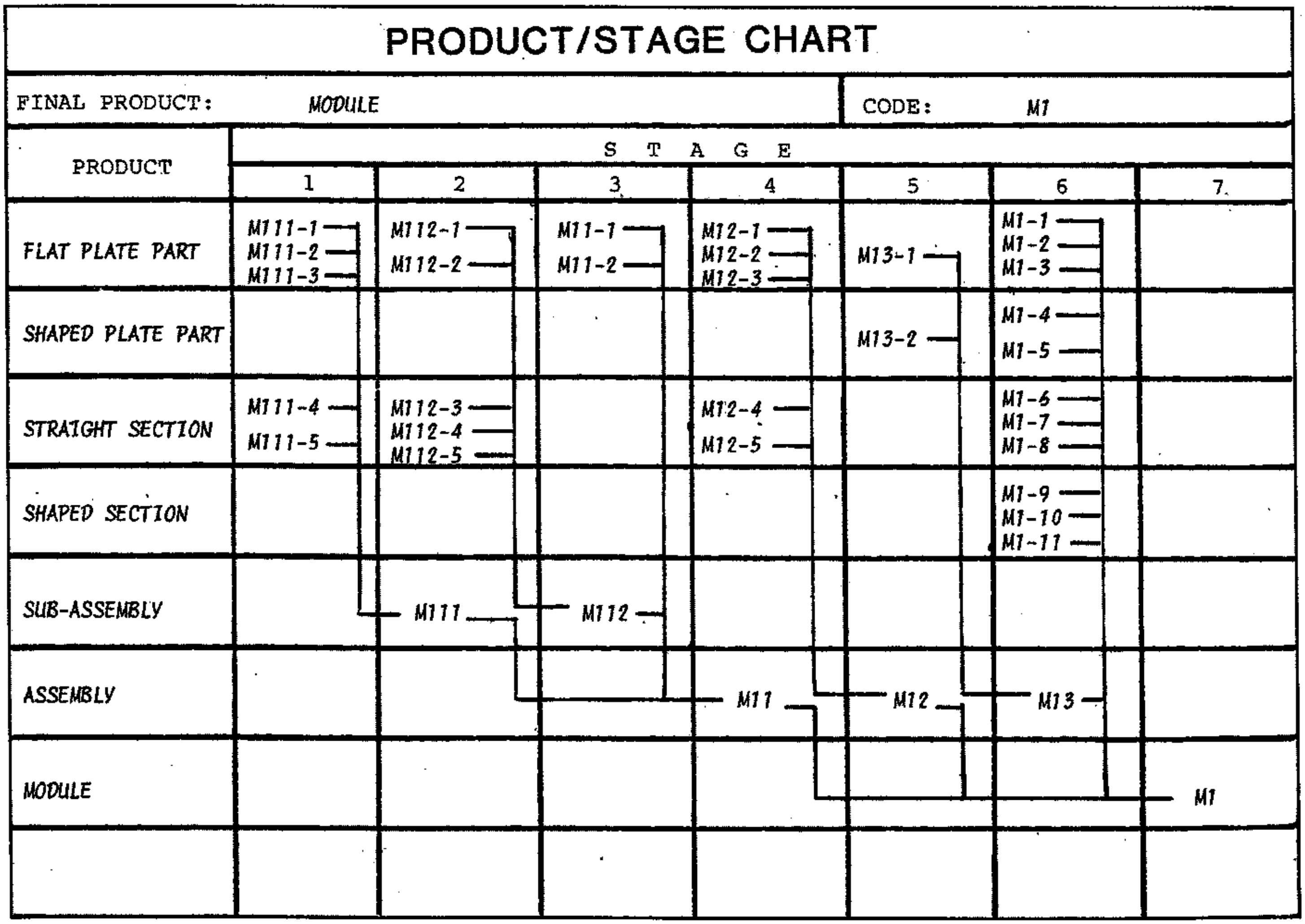


Figure 14.11 Material Definition Phases

This is accomplished by using the most efficient methods of construction while satisfying the many compromises resulting from the conflicting requirements between the shipowner, regulatory and classification rules, and the need to be competitive with other shipyards.

The need is obvious and it should not have been necessary to develop a new science (DFP) to achieve it. However, it seems that ship designers have not, in general, changed with the changes in ship production and satisfactorily responded to the new needs. Many ship design groups continue to work in isolation from shipyard production influence and do not take into account the producibility of their designs.

This is most unfortunate, as it is at this stage in the overall ship design and production process that the cost is being established and where there is the greatest opportunity to favorably, and vice versa, affect it. This is clearly seen from Figure 14.13, which shows that as the process moves from design into engineering, then planning and actual construction, the ability to influence cost, and therefore, achieve cost savings, diminishes. It is therefore essential that ship



PRODUCT/STAGE CHART

FINAL PRODUCT: *MODULE*
CODE: *M1*

PRODUCT	STAGE 1	2	3	4	5	6	7
FLAT PLATE PART	*M111-1* *M111-2* *M111-3*	*M112-1* *M112-2*	*M11-1* *M11-2*	*M12-1* *M12-2* *M12-3*	*M13-1*	*M1-1* *M1-2* *M1-3*	
SHAPED PLATE PART					*M13-2*	*M1-4* *M1-5*	
STRAIGHT SECTION	*M111-4* *M111-5*	*M112-3* *M112-4* *M112-5*		*M12-4* *M12-5*		*M1-6* *M1-7* *M1-8*	
SHAPED SECTION						*M1-9* *M1-10* *M1-11*	
SUB-ASSEMBLY		*M111*	*M112*				
ASSEMBLY				*M11*	*M12*	*M13*	
MODULE							*M1*

Figure 14.12 Product/Stage Chart

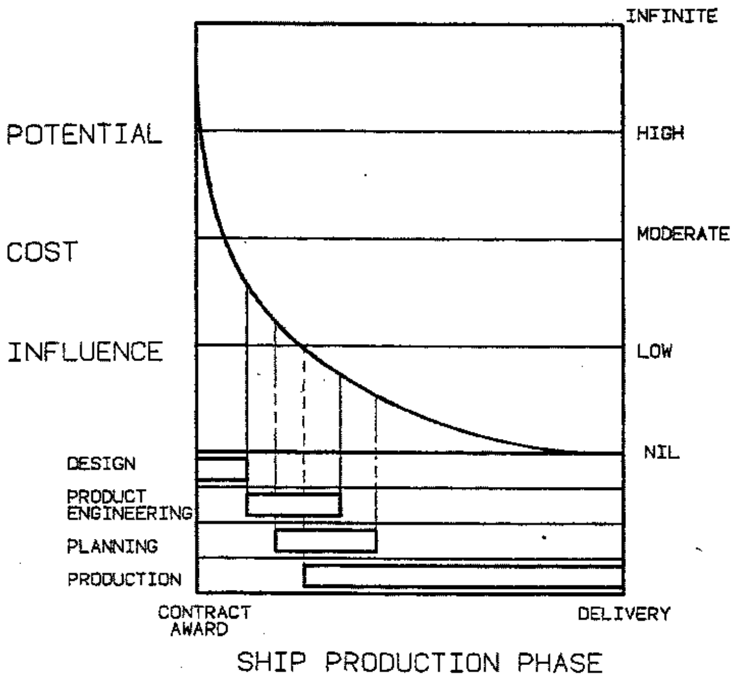


Figure 14.13 Potential Cost Influence as Design and Build Phase Progresses

design agents develop a way to correct the current lack of production considerations in their designs for all future contracts in which they are involved. At the start of any contract design they should find out from the customer the shipyards that will be invited to bid for the contract, and spend time with the planning and production staffs of these shipyards to develop an understanding of their facilities, planning and preferred construction approaches and any standards developed by the shipyards.

To accomplish this, the ship designer must become better educated in ship production processes and their relative costs.

More recently, Design for Production has been defined as the deliberate act of designing a product to meet its specified technical and operational requirements and quality so that the production costs will be minimal through low work content and ease of fabrication and assembly.

Design for Production is not:

- improvements in facilities,
- improvements in materials, and
- alterantive shipboard equipment;

UNLESS

- DFP was the major driver in bringing about the change.

It is simply addressing the fact that today's ship designers have a commitment to assess their ship designs for high productivity. To do this, they must consider the relative efficiencies of available production processes and construction methods. This places additional responsibility on the designer. However, it must be willingly accepted, because if it is not, the effect on production costs can be fatal to a shipyard. Today's ship designer has both the opportunity and the obligation to design production-friendly ships. The ship designer in isolation cannot seize this opportunity. It is only possible through an awareness of the shipyard facilities and methods used in the shipyard that will build the design. This necessitates continual interface and cooperation between the engineering, planning, and production departments.

The principal problem for Design for Production is the development of this knowledge for the ship designers. This can be accomplished by the development of *Shipbuilding Policy* for each shipyard and *Build Strategy* for each ship to be built (see section 14.4). Ship designers constantly refer to the ship's *Contract Specifications* for the technical and quality requirements of the ship. It is suggested that they should likewise refer constantly to the Shipbuilding Policy and the Build Strategy for how the ship is to be constructed and to design accordingly. More details on both can be found in (15). While the Contract Design is progressing, the Build Strategy would be developed in parallel. The completion of the design during the Functional Design phase must obviously be in accordance with the Build Strategy.

Two recent papers (16,17), by the same authors, on Ship Structural Design for Production, state that its application is ineffective without a meaningful merit factor and that such a factor must be based on a production costing technique capable of taking into account different physical design differences as well as production processes. While much can be gained from the intuitive approach by knowledgeable and experienced designers, with and without input from planning and production, it is still subject to differences of opinion, and the danger of errors of omission. That is, some aspect, process or work task can be left out of the consideration. It would obviously be better to use an industry, or at least, a company, accepted Merit Factor for the basis of the analysis. Unfortunately, there is no merit factor currently available, and it is only necessary to try to discuss this matter with an experienced ship construction estimator to appreciate the extent of this problem.

Most Ship Cost Estimating systems do not consider the design or construction tasks in sufficient detail to be able to be used as a Design for Ship Production Merit Factor. For example, for structure the cost estimating system may use combinations of total ship or block steel weight, complexity factors, average weight per unit area and joint weld length. These are not enough for a merit factor that will allow changes in detail to be compared. What is required is a method that takes into account all the design and production factors that can differ. At the present time such a method does not exist, nor is there an existing historical data library from which it could be developed. It is necessary, therefore, to develop an approach, and then collect the data required to use the approach. This is where the application of Work Measurement and Method Study techniques can help.

From the previous description, it should be obvious that what is proposed is not a simple exercise. Significant effort would be involved as well as the potential to interrupt normal work in a shipyard. Nevertheless, it is necessary that the approach be completely developed if full benefits are to be obtained from the use of Design for Ship Production.

This has been attempted by J. Wolfram (18), for welding man-hours in a shipyard panel shop. The resulting equation is

$$\text{Welding Man-hours} = 2.79 \times \text{NPS} + 0.0215 \times \text{JLFB} \times t_{FB} + 0.097 \times \text{JLCB} \times t_{CB} + 0.017 \times \text{JLF} \times \text{FCSA}$$

where

NPS = number of panel starts
JLFB = joint weld length of flat panel butts
t_{FB} = thickness of flat panels
JLCB = joint weld length of curved panel butts
t_{CB} = thickness of curved panels
JLF = joint weld length for fillet welds
FCSA = cross-sectional area for fillet welds

The same approach could be used for all other shipbuilding processes with the final system becoming an effective labor estimating tool for both new construction cost estimating and trade-off analysis. 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. Figure 14.14 shows a form that can be used to perform a manual calculation for work content and cost for a structural part.

Similar forms would be used for sections, subassemblies, assemblies, blocks and the erection and joining of the blocks. Obviously, the calculation could be programmed and run on a computer, and it is even feasible to link the computer program with an interactive computer graphics system, which would present the desired merit factor for each design detail, as it was developed. Similar forms, or programs, could be developed for all other ship systems and production processes.

Design for Ship Production can, therefore, be applied in a number of ways, varying from a simple ease of fabrication *gut feeling* decision to a very detailed analysis using work measurement and method study techniques. The latter are considered the domain of Industrial Engineering, but a good understanding of them will improve the ship designer's ability to prepare the best production oriented designs for a given shipyard.

Most ship designers will not have either the experience or the time to use such techniques in their normal design decision process. However, if an Industrial Engineering capability exists in their shipyard, they should take every opportunity to benefit from it. If possible, they should work with the Industrial Engineers to arrive at the best design for their shipyard. If such a capability does not exist in the shipyard or it is too busy with the many other areas they are involved in, and it is not reoriented by management, Design for Ship Production can still be performed. The ship designer with a team from planning and production can develop the different ways to design a detail and rank it on the basis of producibilty and cost aspects.

When complete, the selected *best* design and the selection analysis can be sent to the other departments that are involved in the process, for their review and concurrence. It is strongly recommended that a Design for Ship Production team be established to review and maintain a shipyard's existing standards, and at an early stage of all new ship design development to ensure that the design will be the most producible and cost-effective design for their shipyard. Table 14.I is suggested as a minimum procedure for applying Design for Ship Production based on experience and intuition of such a team.

In some shipyards, the only design that is performed inhouse, is the *Production Design,* such as working drawings for the shipyard and any calculations necessary to prepare them, which will be based on an owner provided Contract Design and Specifications.

The subject of ship design is well covered in many books and in the transactions of the naval architecture and marine engineering professional societies. It will be discussed only to the extent necessary for the incorporation of Design for Ship Production.

14.3.1 DFP Principles

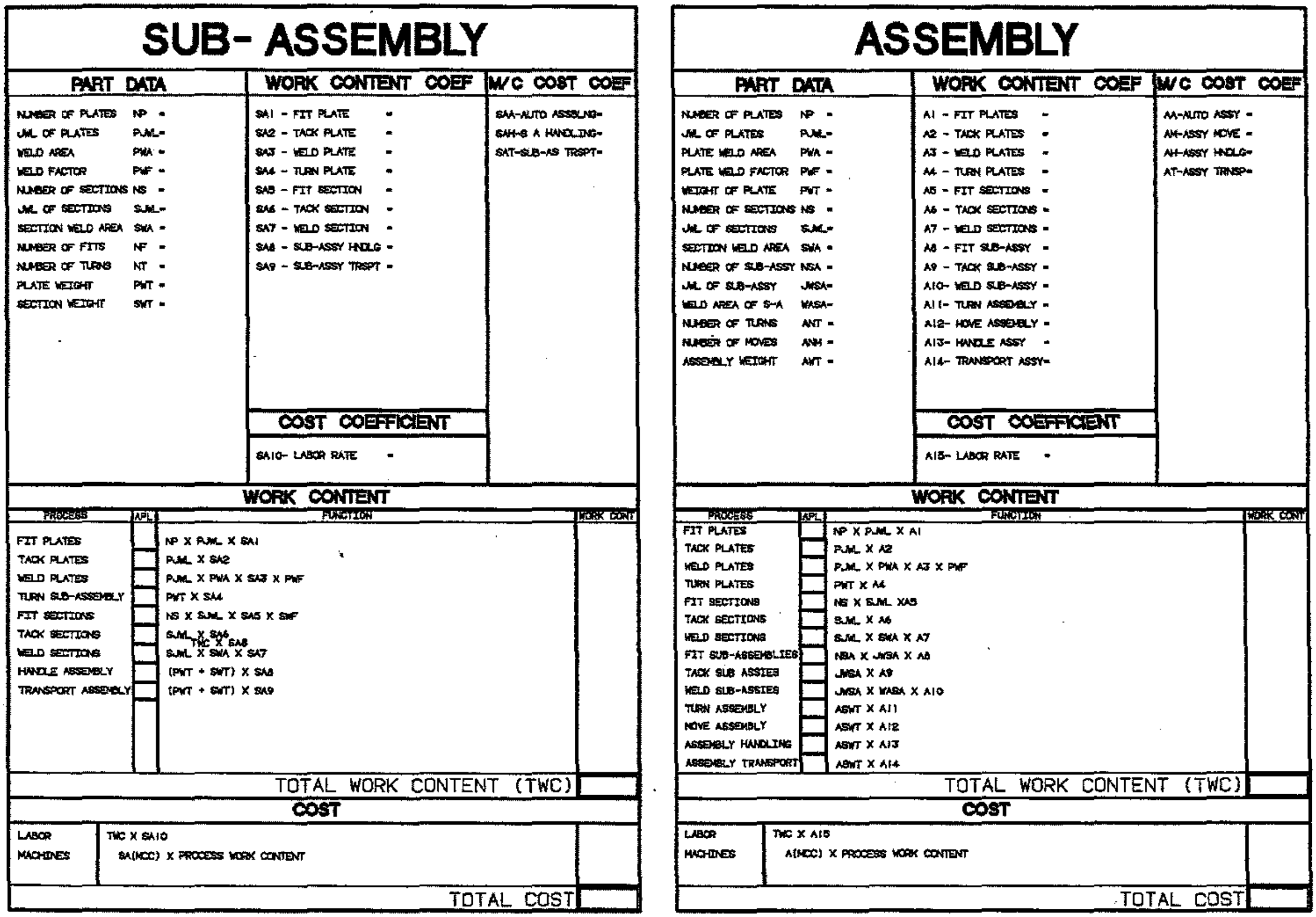
There are two main principles for DFP for ships, namely

1. all design should strive for simplicity, and
2. all design should be the best suitable for a given shipyard facility.

These can be further expanded as follows:

Simplicity in Design

- minimum number of parts,
- minimum number of parts to be formed,
- reduction of part variability,
- reduction in joint weld length,
- part standardization,
- minimum fitting/fairing of erection joints,



SUB- ASSEMBLY

PART DATA

NUMBER OF PLATES NP =
JWL OF PLATES PJWL=
WELD AREA PWA =
WELD FACTOR PWF =
NUMBER OF SECTIONS NS =
JWL OF SECTIONS SJWL=
SECTION WELD AREA SWA =
NUMBER OF FITS NF =
NUMBER OF TURNS NT =
PLATE WEIGHT PWT =
SECTION WEIGHT SWT =

WORK CONTENT COEF

SA1 - FIT PLATE =
SA2 - TACK PLATE =
SA3 - WELD PLATE =
SA4 - TURN PLATE =
SA5 - FIT SECTION =
SA6 - TACK SECTION =
SA7 - WELD SECTION =
SA8 - SUB-ASSY HNDLG =
SA9 - SUB-ASSY TRSPT =

M/C COST COEF

SAA-AUTO ASSBLNG=
SAH-S A HANDLING=
SAT-SUB-AS TRSPT=

COST COEFFICIENT

SA10- LABOR RATE =

WORK CONTENT

PROCESS	APL	FUNCTION	WORK CONT
FIT PLATES	☐	NP X PJWL X SA1	
TACK PLATES	☐	PJWL X SA2	
WELD PLATES	☐	PJWL X PWA X SA3 X PWF	
TURN SUB-ASSEMBLY	☐	PWT X SA4	
FIT SECTIONS	☐	NS X SJWL X SA5 X SWF	
TACK SECTIONS	☐	SJWL X SA6 TWC X SA8	
WELD SECTIONS	☐	SJWL X SWA X SA7	
HANDLE ASSEMBLY	☐	(PWT + SWT) X SA8	
TRANSPORT ASSEMBLY	☐	(PWT + SWT) X SA9	

TOTAL WORK CONTENT (TWC)

COST

LABOR	TWC X SA10	
MACHINES	SA(MCC) X PROCESS WORK CONTENT	

TOTAL COST

ASSEMBLY

PART DATA

NUMBER OF PLATES NP =
JWL OF PLATES PJWL=
PLATE WELD AREA PWA =
PLATE WELD FACTOR PWF =
WEIGHT OF PLATE PWT =
NUMBER OF SECTIONS NS =
JWL OF SECTIONS SJWL=
SECTION WELD AREA SWA =
NUMBER OF SUB-ASSY NSA =
JWL OF SUB-ASSY JWSA=
WELD AREA OF S-A WASA=
NUMBER OF TURNS ANT =
NUMBER OF MOVES ANM =
ASSEMBLY WEIGHT AWT =

WORK CONTENT COEF

A1 - FIT PLATES =
A2 - TACK PLATES =
A3 - WELD PLATES =
A4 - TURN PLATES =
A5 - FIT SECTIONS =
A6 - TACK SECTIONS =
A7 - WELD SECTIONS =
A8 - FIT SUB-ASSY =
A9 - TACK SUB-ASSY =
A10- WELD SUB-ASSY =
A11- TURN ASSEMBLY =
A12- MOVE ASSEMBLY =
A13- HANDLE ASSY =
A14- TRANSPORT ASSY=

M/C COST COEF

AA-AUTO ASSY =
AM-ASSY MOVE =
AH-ASSY HNDLG=
AT-ASSY TRNSP=

COST COEFFICIENT

A15- LABOR RATE =

WORK CONTENT

PROCESS	APL	FUNCTION	WORK CONT
FIT PLATES	☐	NP X PJWL X A1	
TACK PLATES	☐	PJWL X A2	
WELD PLATES	☐	PJWL X PWA X A3 X PWF	
TURN PLATES	☐	PWT X A4	
FIT SECTIONS	☐	NS X SJWL XA5	
TACK SECTIONS	☐	SJWL X A6	
WELD SECTIONS	☐	SJWL X SWA X A7	
FIT SUB-ASSEMBLIES	☐	NSA X JWSA X A8	
TACK SUB ASSIES	☐	JWSA X A9	
WELD SUB-ASSIES	☐	JWSA X WASA X A10	
TURN ASSEMBLY	☐	ASWT X A11	
MOVE ASSEMBLY	☐	ASWT X A12	
ASSEMBLY HANDLING	☐	ASWT X A13	
ASSEMBLY TRANSPORT	☐	ASWT X A14	

TOTAL WORK CONTENT (TWC)

COST

LABOR	TWC X A15	
MACHINES	A(MCC) X PROCESS WORK CONTENT	

TOTAL COST

Figure 14.14 Structural Work Content and Cost Calculation Form

- elimination of need for highly accurate fitting,
- integration of structure and outfit,
- elimination of need for staging, and
- consideration of access.

Matching to Shipyard Facilities

- checking that blocks and machinery package units and outfitted blocks are within shipyard lifting capability,
- assembly and block sizes fit panel line, workstations and door openings,
- use maximum plate sizes and corresponding block breaks to minimize connecting joint weld length, and
- maximize design for in-shop versus on-ship work.

14.3.2 Tailoring Design to Facilities

While it is beneficial for a shipyard to be able to build any ship design, it is a well known fact that such general capability will increase the cost to build the shipowner's custom design than one which is designed to make best use of a shipyard's facilities. Obvious shipyard imposed requirements are:

- ship dimensions and limits,
- block maximum weight,
- block maximum size,
- panel maximum size, and
- panel line turning and rotating capabilities.

Obviously, a shipyard would be unwise to attempt to build a ship which was longer or wider than the building berths and/or docks, or higher than the cranes could reach. Of course, this would not be so if part of the building plan was to improve the facilities.

The block maximum weight can be dictated by berth or shop crane capacity, and/or transporter capacity; also, by advanced outfitting and any temporary bracing and lifting gear used for the lift. The block maximum size will depend on access throughout the shipyard for the blocks from as-

TABLE 14.1 Application of Design for Ship Production

1. Examine Existing Design
   a) count the number of unique parts
   b) count the total number of parts
   c) count number, type and position of joints
   d) evaluate complexity of design
      - simple measurement
      - simple manual layout
      - complicated manual layout
      - CAD/CAM applicability
      - required manual processing
      - required machine processing
   e) Producibility aspects
      - self-aligning and supporting
      - need for jigs and fixtures
      - work position
      - Number of turns and moves
      - Aids in dimensional control
      - Space access and staging
      - Standardization
      - number of compartments entered to complete work
2. Examine Alternative Design(s) in same manner
3. Select the Design that meets the objective of Design for Production, which is: *The reduction of production cost to the minimum possible through minimum work content and ease of fabrication, while meeting the design performance and quality requirements.*

sembly to erection, shop door sizes and the shipyard's maximum plate size. The panel maximum size will depend on panel line limits as well as any access limits. It will also be impacted by whether the panels need to be turned and/or rotated. A panel line with no rotation capability can achieve the same results by vertical plate straking of shell and bulkheads when the ship is transversely framed and the bulkheads vertically stiffened.

Not so obvious and often ignored requirements are:

- maximum berth loading,
- spread of launchways, and
- maximum launch pressure on the hull.

The maximum berth loading could affect the extent of outfitting before launch and thus the productivity achieved in building the ship. Heavy concentrated weights, such as propulsion engines and gears, and independent LNG tanks may not be able to be installed until the ship is afloat. The spread of the launchways should be matched by basic ship's structure, such as longitudinal girders, in order to eliminate the need for any additional temporary strengthening, which only adds to the work content. Likewise, the structure of the ship in way of the area subjected to maximum way end pressure and the fore poppet should be designed to withstand these loads without the need for additional temporary structure.

Whatever the facility requirements on the design, it is obvious that they must be fully industrial engineered, well documented and communicated to the designers. The use of computer simulation techniques (19) can serve as both an educational and informational tool to give ship designers a better understanding of the capabilities of a shipyard. The already stated concept of Shipyard Specifications of parallel importance and applicability as the usual Contract Ship Specifications would also be an effective way to accomplish the transmission of the information to the ship designers. However, it would not in itself assure production-oriented designs. To assure this, it is essential that the ship designers be educated and trained in the field of Design for Ship Production.

14.3.3 Design for Production in Basic Design

Basic Design covers all design from Conceptual through to at least Contract Design, that is *concept, preliminary*, and *contract design*. It is proposed that it should also cover *Functional Design*. Functional design is the phase where the contract design is expanded to encompass all design calculations, drawings, and decisions, thus defining all systems and required material.

Design for Production must be applied during basic design. The structural breakdown definition as well as zone and advanced outfitting *On-umit, On-block,* and *On-board* definitions must be decided during this phase.

The other phase of design, conducted after contract award, is usually called Detailed Design. It usually covers all remaining activities to document the design. It usually does not incorporate production considerations. The author uses the term Product Engineering to differentiate between the traditional Detailed Design and production-oriented documentation.

Product Engineering covers all tasks required to prepare the technical information to be transmitted to production and other shipyard groups to assist and direct the construction of the ship. It is divided into two phases. The first, transitional design is the task of integrating all design information into complete zone design arrangements and to complete the ordering/assigning of all materials. The second, work station/zone information preparation, is the task of providing all drawings, sketches, parts lists, process instructions and production aids (such as numerical control [N/C] tape for plate burning/marking and pipe fabrication) required by production and other service departments to construct the ship.

Figures 14.15 and 14.16 show the relationship of Basic and Production Design and the lower classes such as Concept Design, Preliminary Design, etc.

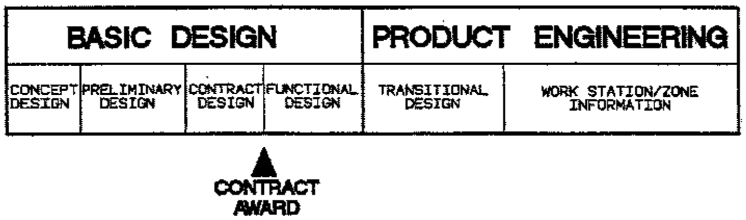


Figure 14.15 Design Stages

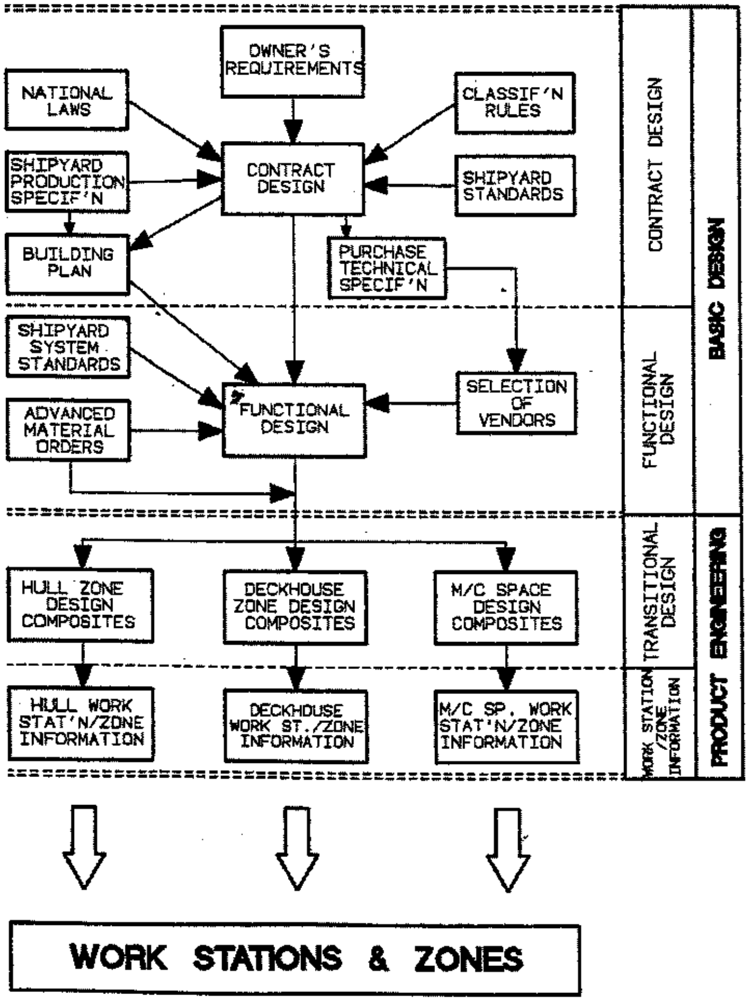


Figure 14.16 Design Flow

Throughout basic design, the tasks are accomplished on a system basis, whereas throughout product engineering, the tasks are accomplished on a zone basis for transitional design and a work station/zone basis for work station/zone information.

14.3.3.1 Hull form design

A Lines Drawing developed without consideration of the impact on production of its various work content aspects can increase the work content significantly, and prevent the achievement of high productivity and lowest construction cost. Double and reverse curvature surfaces, *clipper bows*, *cruiser sterns*, keel, stem and stern half sidings, and inappropriately located *knuckles/chines* all add work content.

The development of low resistance and efficient propulsion lines is a highly specialized field and often is performed by naval architects and hydrodynamicists with very little shipyard engineering and production experience. While it is not proposed that consideration of the producibility aspects be allowed to overrule the lines designer's decision where it could adversely affect the efficient operation of the ship after it is delivered, it is proposed that lines designers should obtain a better understanding of the impact their design decisions have on the producibility of the ship. They should then incorporate producibility improvement aspects that have a high work content reduction and a small, if any, adverse impact on hydrodynamic and propulsion efficiency. In this context, it should be remembered that a seagoing ship hardly ever operates in smooth water, and that the impact of any producibility change should be considered in its seagoing environment, and not the result of a smooth water model towing tank test.

Ship hull form design has to 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. Producibility aspects depend on the production process and the material used. It is therefore important to understand at least the most important implications of production techniques and materials for design. Changing technologies and materials lead to different *optimum* results.

Prior to the mid-19th century most ships were made of wood. Wood limited the size of the ships, but the limiting fairing properties of the material resulted in automatically *fair* ship hulls with usually good hydrodynamic properties. Wooden hulls featured rather smooth curvature. Basically the same principles for hull form design were applied to the first steel ships. Even full hull forms were still designed without flat bottom or sides even in the early 20th century. Ship designers only gradually realized that hull design had to take into account producibility aspects, and these in turn changed with materials (from wood to steel) and production processes (from riveting to welding). But eventually ship designers realized that steel hulls for full hull forms, that is tanker and bulk carrier, could be designed with large parallel midbodies with rather rectangular cross sections without seriously decreasing the hydrodynamic properties of the ship.

New materials such as fiber-reinforced plastics, and new production technologies such as laser welding or adhesive bonding may yet lead to another change in *best* hull forms, but only aspects of producibility for welded steel hulls using shipyard technology widely available today (2003) will be considered in this chapter. Nevertheless, the example of material technology shift from wooden to steel ships impact on hull form should teach us that producibility in design is not a static process, but rather that general principles change as technology and material change.

The *optimum* hull will always be a trade-off of production cost and operation cost subject to various constraints. Production cost depend on available production technology and labor cost. Operation cost depend on fuel prices. In addition, constraints such as delivery times may yet introduce another factor shifting the optimum hull. For example, in times of war it was necessary to produce transport capacity in a very short time favoring hull forms that are easy to produce, while having rather high fuel consumption. Thus the naval architect will always have to find an appropriate trade-off and no general rule for all times can be given.

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, such as in parts of the bottom or side plating in the parallel midbody of the hull.

In modern shipbuilding, there are two main processes in plate forming and stiffener forming:

1. *Cold forming* involves using rolls and presses to shape plates and stiffeners, and
2. *Thermal forming* involves line heating using torches and lasers.

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. 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.

In the forming of many curved plates, the required shape exceeds the capacity of cold forming techniques. In these cases, heating the plates in a furnace to make them more malleable may be required. 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. Line heating is the process of heating, by a narrow heat source such as an oxygen flame torch, and cooling the upper surface, by a stream of water, a plate in a series of lines to produce a the desired shape. Procedures for line heating depend on material type and size. Line heating is often used to finish a plate to the desired shape. Line heating is a very labor intensive and high skill process. Computer controlled line heating machines have been developed by some Japanese shipyards reduce the work, and full automation appears possible for the future (20).

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. This is because of the high manual and skill level required to form the plates to their required shape. Because it is a manual process requiring high skill, it is not a repeatable process and suffers from inaccuracy. That this is recognized as a major problem can be seen from the efforts over the years to eliminate/reduce the extent of curved shell plates. Therefore, when preparing a lines drawing, the following items must be considered from a producibility point of view.

Historical review of simplified hull forms Producibility in design of the hull form of steel ships is not a new concept. Among the historical attempts in this direction are:

- William McEntee (21) presented a paper on probably the first major work directed specifically towards simplifying hull forms stimulated by the need during World War I to produce quickly, more transport capacity. In his work, McEntee tested three sets of models representing both conventional and simplified hull forms for a barge, a cargo ship, and a collier. The degree of simplification consisted of using vertical wall-sided sections over the entire length, straight bottom sections with no deadrise forward, a plumb bow, and the bottom and sides joined by circular arcs McEntee concluded, based on the results of his model tests, that simplified hull forms could be designed with calm-water resistance about the same as conventional forms. (The general validity of this conclusion especially for modern hull forms has to be doubted.)

- A year later, Sadler (22) gave a comprehensive report of his investigations concerning the resistance penalty entailed by simplifying hull forms. The forms examined were even simpler than those of McEntee. Even with such very elementary forms, Sadler concluded that vessels with straight frames may have the same resistance as faired shapes.
- Similar work in Great Britain resulted in the construction of the *N* (National) type standard ship during World War I (23). The British investigations basically supported the conclusions reached by McEntee and Sadler. As the wartime crisis abated, the interest in simplifying hull forms also subsided. However, the discussion about various ideas did not stop completely (24, 25).
- In 1919, ship made of concrete were built due to the shortage of steel. The material and production technology required rather simple hull forms which would see a renaissance in World War II.
- In a survey paper, John McGovern (24) discussed the emerging technology of fully welded ships and its implications on ship hull forms. He proposed a simplified hull form. All frames were straight except for the circular bilge and part of the forecastle. McGovern found again that the simplified form had only marginal hydrodynamic disadvantages compared to a fully faired hull form: *Two series of models were tested in the experimental tank. The selected model was such that the speed and resistance qualities of this form were shown to be equivalent to models of the best ordinary form having the same dimensions and displacement.*
- World War II again saw renewed activity in the area of simplified hull forms. Although most construction of

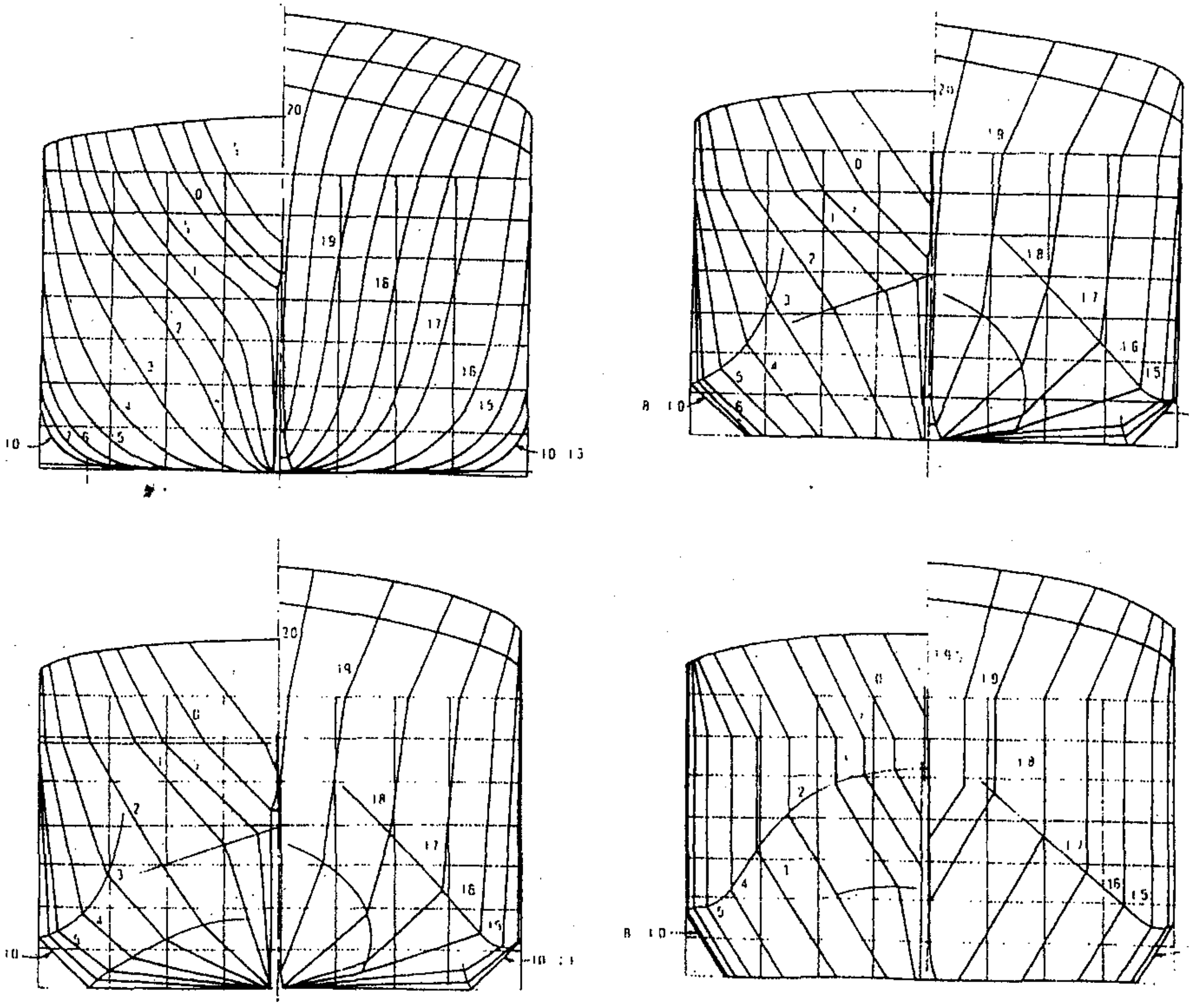


Figure 14.17 Body Plans of Johnson's (1964) "71" Series (26)

simplified hulls involved small craft and auxiliaries, the U.S. Maritime Commission had 24 C1-S-D1 concrete steamers constructed in 1943–1944, Post-war interest subsided again, especially for oceangoing ships.

- Johnson (26) conducted extensive series of model tests to investigate the resistance and propulsion of simplified hull forms in calm water. Johnson noted that chines or knuckle lines should be aligned along streamlines to avoid high drag due to vortex shedding. To accomplish this, he began with a ship of conventional form, found the streamlines, and then designed a ship with straight frames with general character close to the conventional form. He investigated a series of successively simplified hull forms (Figure 14.17). Two series were investigated, one with block coefficient 0.71, one with block coefficient 0.82. For the fuller hull, the power requirements increased by at least 16%. However, for the hull with block coefficient 0.71, the moderate simplification of the *B* version had 4.7% power reduction at design speed and draft! (The extreme simplified form *D* had a 39.8% increase in power requirement.) At non-design draft and trim the performance was not superior, but still comparable to that of the original round form.
- The *Pioneer* hull form developed and patented by Blohm & Voss in Hamburg featured only flat plates on the hull except for the regions on the ship ends, Figure 14.18 (27–29). 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. In addition, Kiss (30) concluded, based on his analysis, that the savings in hull construction would not be able to offset the cost for fuel and power plant increases.

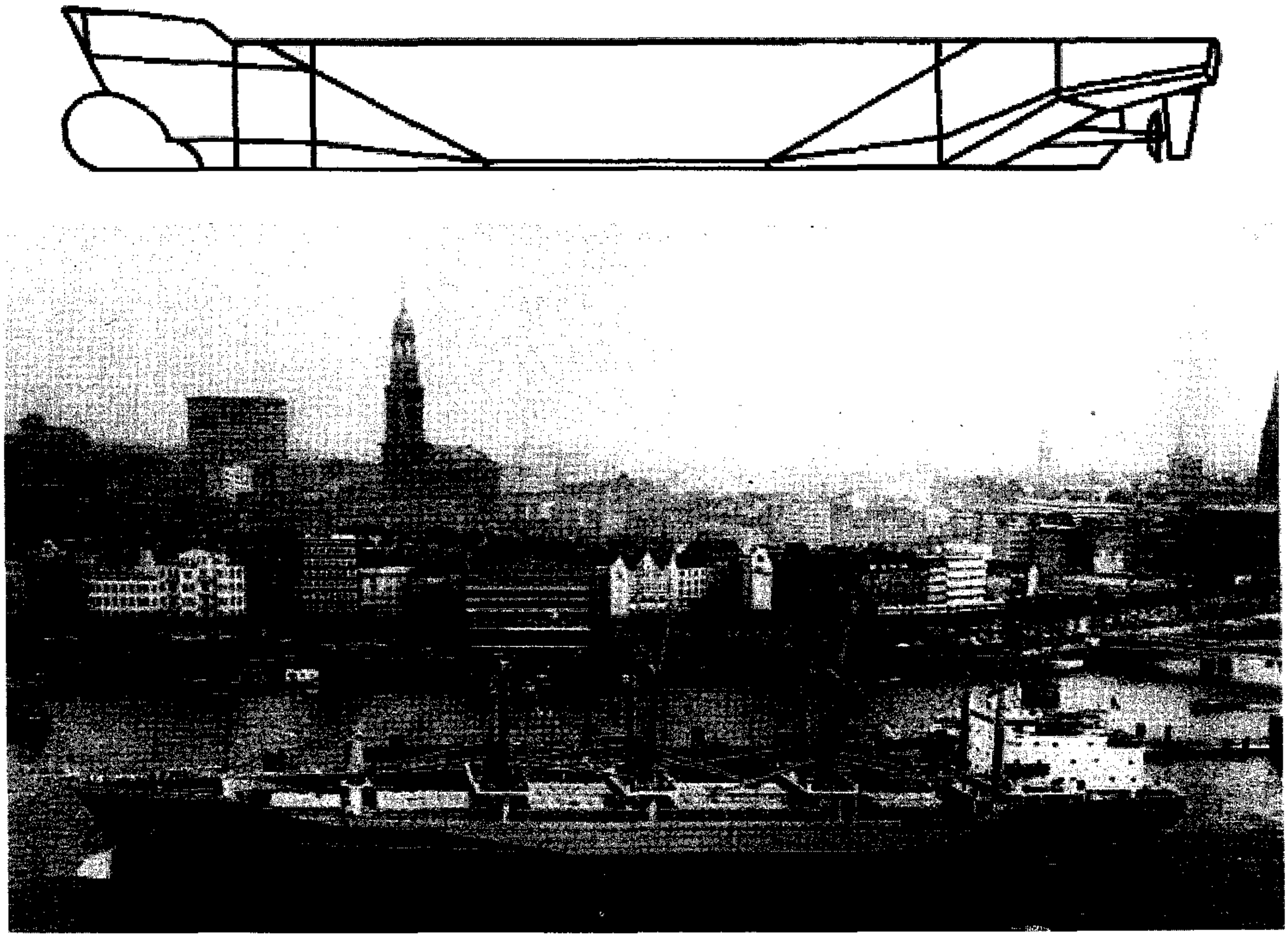


Figure 14.18 *Pioneer* ship of Blohm & Voss

- The Condock I featured many flat plates also in the regions on the ship ends (31,32). The bilge radius was constant over the whole ship length. The centers of the bilge radii were located, except for some transition zones, on straight lines. The stern ended in a flat region. This minimized the bending work for the hull plates.
- The U.S. Maritime Administration conducted research on a low-cost, general cargo ship, simplified and designed for mass production to support the transport demands during the Vietnam war. The research resulted in the Pacer design (33).
- In 1969, Mario Andrea patented an extremely simplified hull, the *helical ship*. The helical ship consisted of flat plates, plates with curvature in a single plane, and rectangular sections with the exception of the underwater portions of bow and stern, which were helical in shape. Preliminary model tests indicated again a drastic increase in power requirements outweighing any improvements in design.
- Burmeister & Wain developed a hull design for bulkers and OBOs which, except for small regions at the ship ends, consists of single-curvature plates (Figure 14.19) (34). The bow was designed parabolically with straight sections.
- Schenzle (35) presents in the Indosail project (Figure 14.20), a hull form consisting predominantly of single-curvature and flat plates.
- Wilkins et al. (36) describe a ship design for a U.S. Navy amphibious assault ship. The whole design was re-assessed in terms of producibility. The curvature of the hull reduced introducing some knuckles. The sections in the foreship were considerably straightened, the bulbous bow simplified. Many of the plates were flat or geometrically developable (conical or cylindrical). The most extensive simplifications were implemented above the waterline.
- The EconoForm design was developed in the mid-1990s and features all developable surfaces. Several similar designs 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.

Hull curvature—a brief review of concepts The local curvature of the hull to a large extent determines the amount of forming needed and thus the cost of producing a particular hull segment. The typical shapes of plating found on the hull of ships are shown in Figure 14.21.

Some concepts of hull form design for producibility thus follows directly from an analysis of hull curvature properties.

The curvature in any point of a surface is defined by the direction and magnitude of the maximum curvature and the minimum curvature perpendicular to the maximum curvature. These two values are denoted as principal curvatures. The sign of the curvature determines whether the surface is convex or concave. 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 involving reverse curvature

A plate is *developable* when one of the principal curvatures is zero over its whole extent. This includes the trivial case when the plate is flat, that is, both principal curvature are zero. In addition, there are a number of important special cases for developable surfaces:

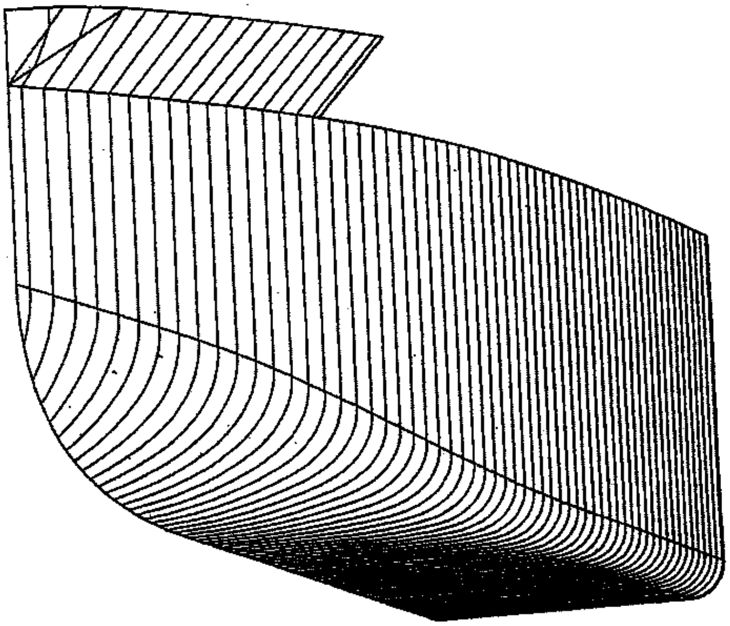


Figure 14.19 OBO Carrier (34)

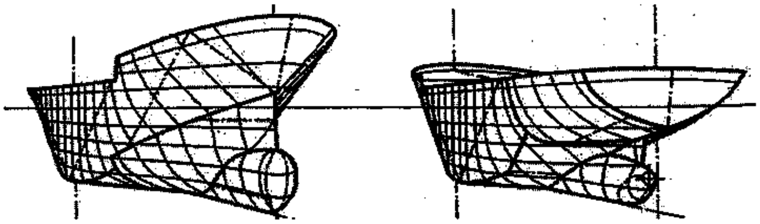


Figure 14.20 Ship Hull Composed only of Developable Surfaces (35)

- cylindrical surfaces; parallel cuts (waterlines or sections) have same contours, and
- conical surfaces; parallel cuts are geometrically similar but of different radii.

Although a sphere is a regular curved surface, it is not a developable surface as we all know from wrapping a sheet of paper around an apple or peeling an orange (Figure 14.22). The production solution is to make a sphere out of triangular cylindrical segments. A typical case of a combination of developable surfaces is the bulbous bow, which can be interpreted as a succession of conical surfaces and cylindrical segments (Figure 14.23). Developable surfaces do not include stretching or contracting of edges. This makes them particularly interesting in terms of producibility as the manufacturing process is then rather simple.

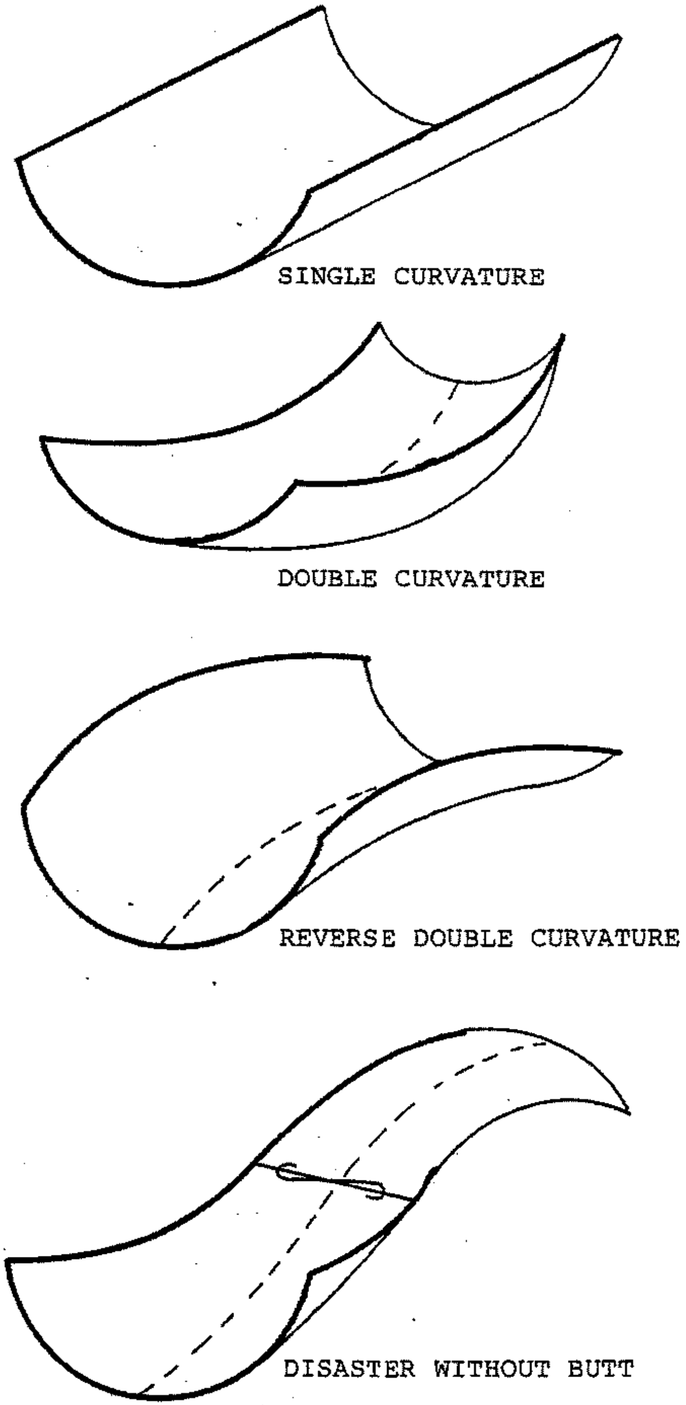


Figure 14.21 Plate Curvature

The complete hull surface of a number of small ships have been designed as developable surfaces. Rational Bezier or B-Splines can be used to produce developable curves, for example, Bodduluri and Ravani (37).

For a more detailed presentation on parametric surfaces and the definitions of surface curvatures, the reader is referred to Farin (38), Nowacki and Kaklis (39).

General producibility principles in ship hull form design

Aspects of easy production for the ship hull can be roughly classified into two groups:

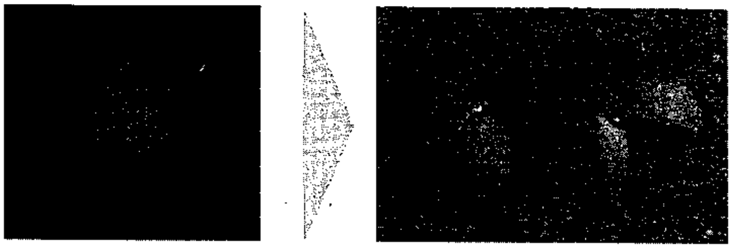


Figure 14.22 A Sphere is not a Developable Surface

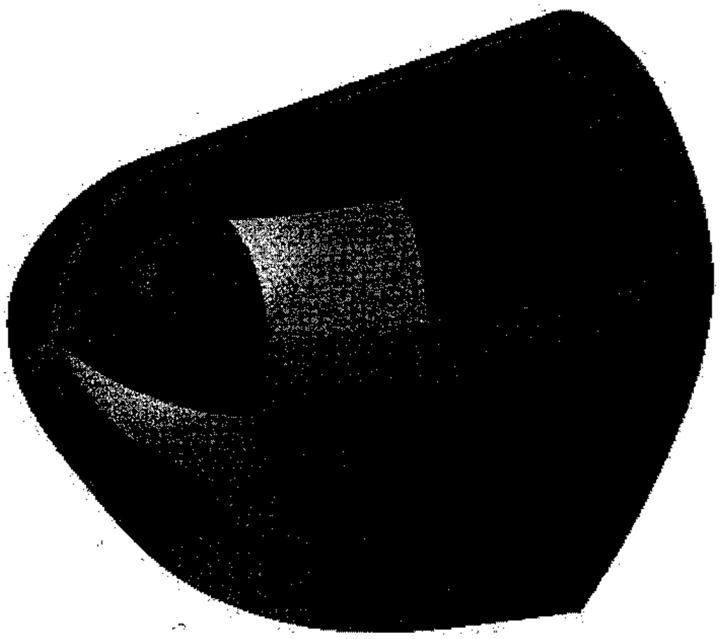


Figure 14.23 Bulbous Bow Designed in FAIRWAY Employing only Patches of Developable Surfaces

1. global aspects which should be considered when choosing the main dimensions, and
2. local aspects which should be considered after the main dimensions have been fixed

The *global aspects*, which are widely known and implemented in modern ship design are (40):

- maximize flat of bottom and flat of side,
- use a straight line stem profile,
- use a flat vertical transom,
- make sure the forefoot shape has fair frame lines,
- select a bilge radius so that one plate width can handle bilge strake,
- 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,
- a *large block coefficient* also increases the amount of flat plates and
- *bilge radius* should be made only so large that one plate can still cover the circumference of the bilge. A small bilge radius reduces the amount of bending for frames and plates.

The *local aspects* are less well known and often not considered to the extent that would be appropriate. But small changes in the hull changes can also improve the producibility of a ship, Kraine and Ingvason (41):

- *Avoid excessive curvature in surfaces on the hull.* That is eliminate any curvature that is beyond the manufacturing and economic capability of the shipyard. All of the available shipbuilding CAD/CAM systems have fairing programs that include tools that show the extent of curvature, such as colored plots (Figures 14.24 and 14.25) and porcupine plots (Figure 14.26). These can be sure that the designed hull form only contains surfaces with curvature within the capability of a given shipyard. In order for the ship designer to be able to do this it is necessary to define a shipyard's capability to handle curved plates. Figures 14.27 and 14.28 show typical data forms that capture this information (42,43).
- *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, Nielsen (13). 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,

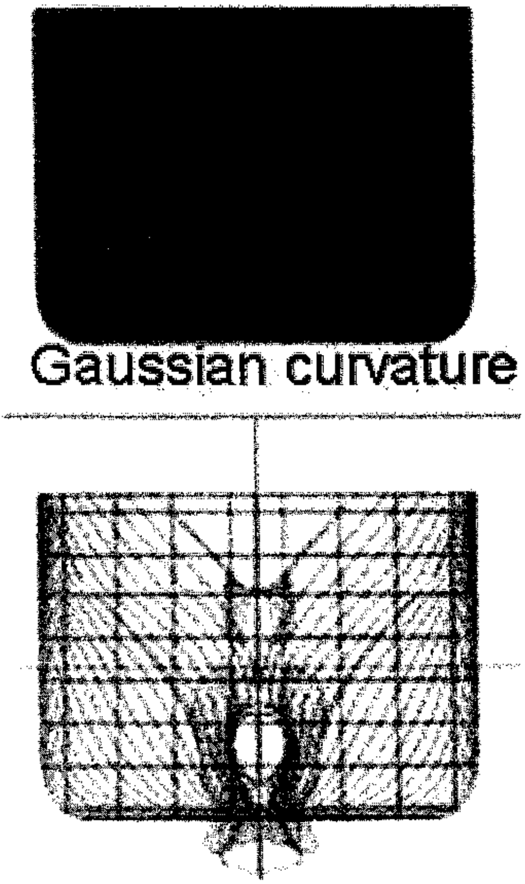


Figure 14.24 Guasian Curvature Plot

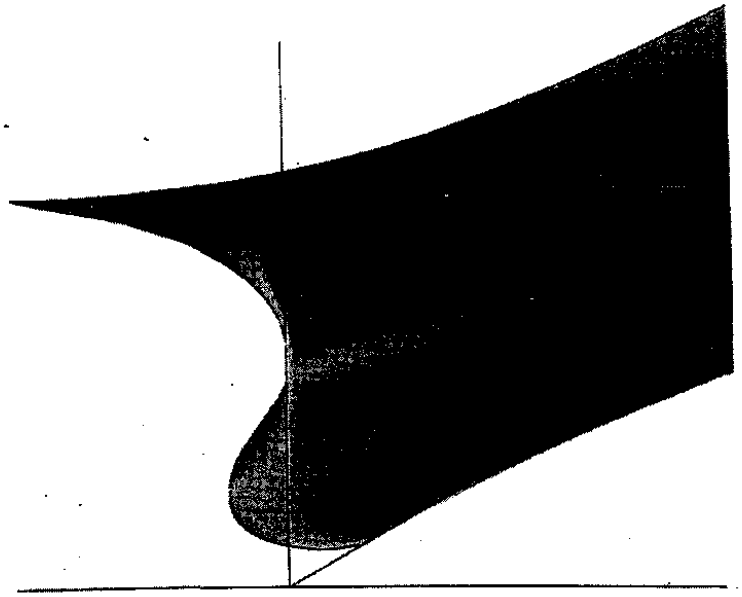


Figure 14.25 Curvature Plot

- *eliminate shape* that forces a decision to use castings in the stem and stern,
- the use of *straight sections* and single-curvature plates improves welding productivity by facilitating the use of automatic welding machines,

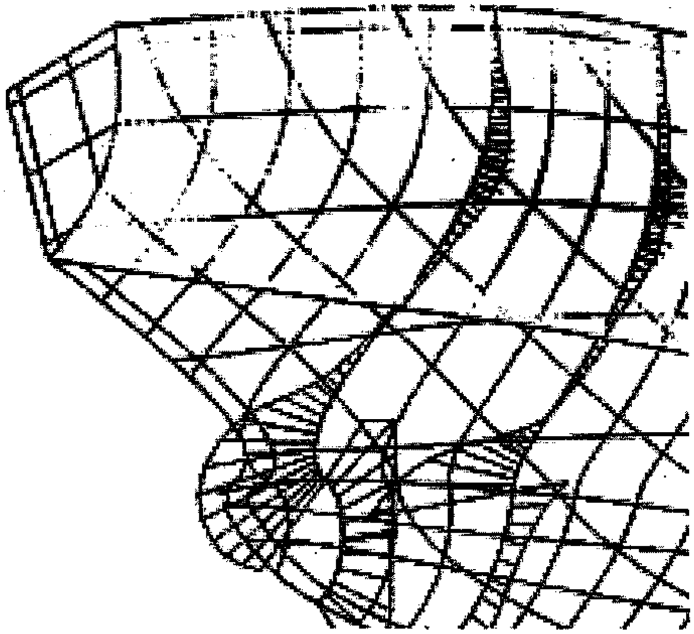


Figure 14.26 Porcupine Curvature Plot

A compound curvature plate can be defined by measuring the following characteristics:

1. Longitudinal Backset Ratio (A/L)
2. Transverse Backset Ratio (B/W)
3. Twist over the length of the plate

These are shown below.

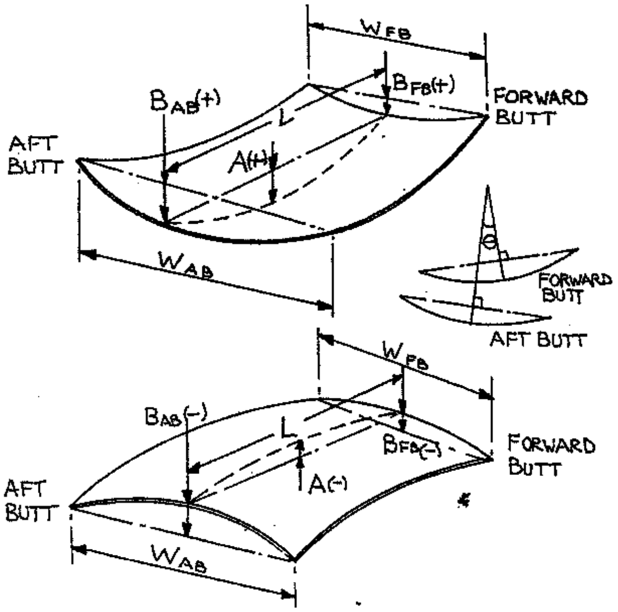
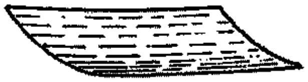
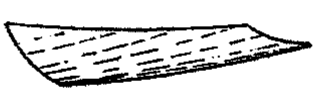


Figure 14.27 Shipyard Plate Curvature Capabilty Information Form: Sheet 1

CLASS	DESCRIPTION	LONGL BS RATIO	TRANSV BS RATIO	TWIST	REQUIRED FORMING	PRODUCIBILITY IMPROVEMENT
A	SMALL BACKSET NO TWIST 	0 ↓ LESS THAN 0.02	0 ↓ LESS THAN 0.08	0 ↓ LESS THAN 10 DEGS	ROLLER OR PRESS	
	SMALL BACKSET AND TWIST 				ROLLER OR PRESS THEN LINE HEATING OR LINE HEATING ONLY	
B	DOUBLE CURVATURE & MEDIUM TWIST 	0.02 ↓ LESS THAN 0.04	0.08 ↓ LESS THAN 0.16	10 DEGS ↓ LESS THAN 30 DEGS	ROLLER OR PRESS THEN LINE HEATING	RESTRAKE TO BRING WITHIN CLASS A CRITERIA
	REVERSE DBLE CURV & MEDIUM TWIST 					
C	LARGE DOUBLE CURVATURE 	MORE THAN 0.04	MORE THAN 0.16	0 ↓ 30 DEGS	ROLLER OR PRESS THEN LINE HEATING SPECIAL TEMPLATES REQUIRED TO ENSURE CORRECT FORMING	SPLIT INTO A NUMBER OF SMALLER PLATES EACH WITHIN CLASS A CRITERIA
	LARGE REVERSE DOUBLE CURVATURE 					
	EXCESSIVE TWIST 	ALL THE ABOVE	ALL THE ABOVE	MORE THAN 30 DEGS	LINE HEATING ONLY	SPLIT INTO TWO PLATES BY PROVIDING BUTT AT SURFACE INFLECTION

NOTE - WHENEVER POSSIBLE DEFINE SHELL PLATES TO BE CLASS A PLATES

Figure 14.28 Shipyard Plate Curvature Capabilty Information Form: Sheet 2