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September 1992
NSRP 0383

THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

1992 Ship Production Symposium Proceedings

Paper No. 7B-2: Evaluating the Producibility of Ship Design Alternatives

U.S. DEPARTMENT OF THE NAVY
CARDEROCK DIVISION,
NAVAL SURFACE WARFARE CENTER

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 1992**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **The National Shipbuilding Research Program, 1992 Ship Production Symposium Proceedings, Paper No. 7B-2: Evaluating the Producibility of Ship Design Alternatives**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center CD Code 2230-Design Integration Tools Bldg 192, Room 128 9500 MacArthur Blvd, Bethesda, MD 20817-5000**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**23**	

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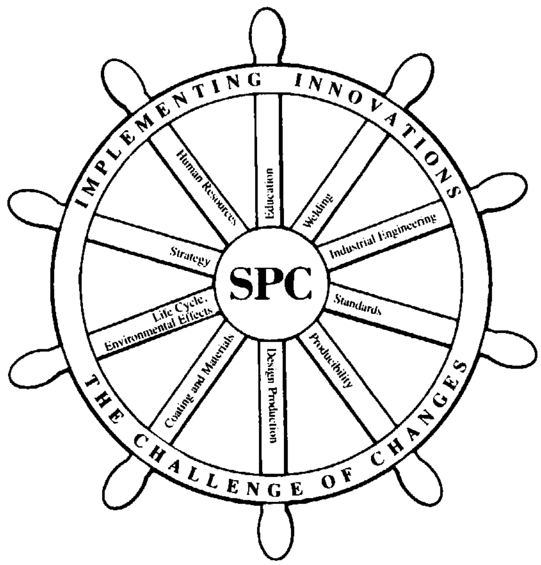

SEPTEMBER 2 - 4, 1992
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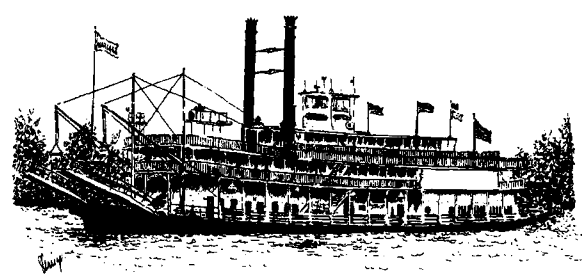

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601 PAVONIA AVENUE, JERSEY CITY, NJ 07306
Paper Presented at the NSRP 1992 Ship Production Symposium, New Orleans Hyatt, Orleans, Louisiana September 2-4, 1992

Evaluating the Producibility of Ship Design Alternatives

No. 7B-2

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ABSTRACT

This paper presents the results of a project that has been carried out under the sponsorship of Panel SP-4, Design/ Production Engineering, of the Ship-Production Committee of the National Shipbuilding Research Program. Two methods for evaluating the producibility of ship designs and/or ship design alternatives have been developed, one of which provides quantitative results in manhours or dollars. The other method provides relative results based on weighting factors developed for specific ship projects and the design phase during which the alternatives are being considered. The second, relative, method also can be used for evaluating all of the other parameters which must be considered in making a decision to proceed with any design change, including total cost, performance, schedule and risk. The two methods are described in some detail and examples of application of each of these two methods to specific design alternatives are presented.

INTRODUCTION

In March 1991, SP-4 authorized a project to develop Producibility Evaluation Criteria for U.S. Navy Ship Designs. The objective of this project was to develop a technique for use by project managers and ship design managers to evaluate the construction cost difference of different design variants. The particular objective was to develop a technique that was based on the actual work content of the design rather than being based on the weight of the resulting design. This distinction is made because most existing cost-estimating techniques utilize weight based factors which are derived from prior designs and are applied to the weight of the design being considered. One consequence of this is that most of the design studies which have been labeled "producibility" studies have concentrated on methods for reducing weight. Many examples can be cited to demonstrate that weight reductions may actually result in increased construction cost. The most extreme result of assuming that cost is a direct function of weight has been the imposition of displacement limitations on some shin types during the design process in the misguided expectation that such limitations would control costs! While recognizing that, in the gross sense, the cost of a product is weight related, the authors were convinced that other techniques could be developed to relate cost more directly with the actual work content of a design.

An additional goal of the project was to provide a method that could be applied at any stage of the design process. It was hoped that the technique developed could be used equally well during early feasibility studies, when few details of a ship design have been developed, as during the construction period, when the design details would be available.

EVALUATION OF PAST PRACTICES

The first three tasks of the project. involved analyzing the content and effectiveness of producibility evaluation methods that had been used on prior programs or that were currently in use for ongoing programs. In carrying out these tasks, team members met with personnel from NavSea project management and design management offices, Supervisor of Shipbuilding Offices, private and public shipyards and private design agents. A listing of various attributes that had been used in the programs carried out under the direction of these organizations was compiled. The results of these meetings were somewhat disappointing, in that the criteria that were being used for evaluating producibility included relatively few items that related to the magnitude of the construction effort. The criteria in use were primarily weight-related factors or performance related factors. Further, it was noted that shipyards do not necessarily make a detailed calculation of cost savings if it is obvious that a change in production practice will reduce manhour5 and cost. Thus, the team was not able to find, in any organization, a method already in use that would accomplish the goals of the project.

DEFINITION OF PRODUCIBILITY

One of the findings from the review of existing methods for evaluating producibility was the recognition that "producibility" usually was being interpreted so broadly that any cost reduction study was labeled as a producibility study. People inherently understand that by improving the "producibility" of a project, the cost of the product will be decreased. However, the converse - that all cost reductions result from having made producibility improvements - is patently invalid. In effect, Producibility was being equated with Productivity. In order to focus the effort of the study team, the following statement was developed:

> Improved producibility involves reduction in the recurring expenditure of resources for constructing a product. Recurring cost is the measure of producibility. There is an inverse relationship between recurring cost and producibility.

This definition identifies the relationship between producibility and cost, but differentiates producibility cost from all other cost items, particularly the non-recurring cost. This distinction is necessary because the non-recurring cost may be prorated over the number of units of the product to be produced, and thus is a variable, while the recurring cost is essentially nonvariant. Producibility cost should include labor cost, material cost and operational cost of the facilities used directly in the production of an item. However, of the operational cost of facilities, only the cost of consumable items has been addressed in the techniques presented herein.

METHODS AND APPLICATIONS

During discussions with personnel of shipyards involved in ship construction, team members obtained lists of design attributes that contribute to reducing construction cost. Most of these had not been used explicitly in any of the existing producibility evaluation methods that were studied. The attributes that were identified were precisely the type of criteria that could be used for evaluating the producibility of a design. This led the team to consider a method for identifying and evaluating criteria known as the Analytical Hierarchy Process (AHP). This method does not require hard data in order to select the preferred choice. However, its results are relative, rather than absolute, and are based upon the subjective opinions of a group of participants with expertise in the field under consideration. The numerical evaluations which it provides do not relate directly to dollars. The potential power of the AHP method is so great that the team decided to apply it to evaluating producibility. However, in addition, the team proceeded to develop a more conventional method, which would provide cost data directly. Consequently, two distinctly different approaches for evaluating the producibility of designs have been developed, each of which has specific advantages.

The techniques discussed above would be considered important and useful if they provided only the cost of producing one specific design compared to the cost of another. However the team realized that the AHP method also was suitable for use in evaluating those elements that enter into a design selection decision, which are schedule, risk, performance and other cost elements. There must be a net positive balance to the consideration of these elements in order to justify a choice between competing designs. Application of the AHP process to the evaluation of these elements, I.e., to the total design decision making process, was the final effort accomplished by the team. Each method was applied to several theoretical and actual producibility issues for validation of the values and techniques used.

THE COST ESTIMATING COMPUTER PROGRAMS

This section describes a technique for determining the cost, in manhours and dollars, to construct a product. The technique is based upon a bottom up, production engineering approach to estimating costs in ship construction and repair.- It is particularly applicable to the analysis of the Producibility of alternate designs and can be applied to small subassemblies as well as to the total ship. Although the complexity of a total ship design might require the expenditure of excessive effort, discrete changes in a total ship design can be evaluated by using the differential method. The technique lends itself equally well to obtaining the total cost of the work or to the differential cost of alternative designs. For producibility questions, the differential cost normally is all that is required.

The work required to prepare a cost estimate of even a simple design can be daunting if performed manually. Further, comparing estimates prepared by different organizations can be extremely difficult, since each organization *may* use different assumptions, approaches and factors for analysis. In order to simplify and standardize the calculation of cost estimates in producibility issues, cost estimating computer programs (CECOPs) for ship construction and repair costs have been developed for those types of shipyard work which are normally the major drivers of construction costs. The CECOPs have been prepared for the high impact trades involved in structural, piping and electrical, as well as for heating, ventilation and air conditioning (HVAC) work. However, this initial group of programs is not all-inclusive. Programs have been prepared only for the major materials utilized in the work in these categories. For example, the structural program has been prepared only for mild steel. aluminum. HY80 and HTS, while the HVAC program is-limited to sheetmetal ducting.

These CECOPs represent the first step in developing a standardized format and methodology for estimating costs of ship construction and repair. As such the programs are intended to establish a common language between the shipyards, the Navy and other organizations. Additional programs will be required to expand the coverage to those other aspects of the work normally performed in a shipyard. These cost estimating forms are only the first step in an evolving process to develop a standardized method of estimating costs in evaluating the producibility aspects of alternate designs.

The CECOPs are in spreadsheet format and are designed for use with Lotus 123 Release 2.0 or later. Translation of the programs to and from other spreadsheet application programs has been accomplished without difficulty. The cost factors used are based upon data and engineering standards obtained from various sources. The contributions to this effort by the U.S. Naval Shipbuilding Scheduling Office and Philadelphia Naval Shipyard are particularly appreciated. It is fully recognized, however, that the data contained in the current version of the programs provide only a reasonable starting point and that extensive revisions and expansions can be expected after other organizations review and apply the programs.

Basic Concept

The basic concept of the cost estimating programs is to estimate costs by identifying all of the discrete work processes to be used when constructing the design under consideration and to apply factors, from engineered standards and other data, which determine the manhours required to accomplish each work process. The factors used take into account whether the work is accomplished during the most efficient work stage or at a later point in the construction process. The sum of the manhours required to complete all of the work processes involved, multiplied by the cost per manhour, generates the direct labor cost. By adding the support labor cost and material costs to the direct labor cost, the total cost is obtained.

The steps in the process follow.

1. Select the design feature to be analyzed.

2. Identify the shipyard work processes which would be used in the production of the design feature.

3. Identify the trades required to perform the work.

4. Determine and apply the engineered standards for each work process.

5. Apply a factor to reflect the increased difficulty of performing the work at a stage other than the ideal stage, on which the engineered standard is based.

6. Apply a factor for the support man-hours required.

7. Convert manhours to dollars.

a. Estimate material costs from the bill of material.

9. Total the cost for constructing the design.

10. Compare the cost with alternate design construction costs.

The differential method uses a simplified approach, which considers only the differences in alternative designs and limits the analysis to those differences.

Spreadsheet Format

Table I illustrates the elements of the CECOP forms, each of which is in a similar format. The details of all of the forms developed are provided in Reference (1).

The heading of each form defines the type of system being covered and provides fields for the entering the size of the material to be used. When the material size is entered into the field at the top of the form, all of the values in the process factor column are automatically entered, from a cost estimating data table in which the engineered standards for each material size have been provided. Table II provides the data used for the mild steel piping form. Data for the other

COST ESTIMATING FORM FOR PIPING (P2)

FILEPIP2CFE
2/20/92

PROJECT : EXAMPLE #l -FITTINGS
FILE : EXAMPLE1

PIPE MATERIAL : CARBON STEEL
DIAMETER: 2 IPS
SCHEDULE : 40

WORK PROCESS	WORK UNITS	PROCESS FACTOR (MNHRS/WK UNIT)	UNIT AMOUNT	ACTUAL STAGE	STANDARD STAGE	ACTUAL FACTOR	STANDARD FACTOR	MANHOURS REQUIRED
1 OBTAIN MATERIAL								
RECEIPT & PREP	PIECE	1.00	4	1	1	1.0	1.0	4.0
2 CUTTING								
MACHINE	COT	.05	14	1	1	1.0	1.0	.7
MANUAL	COT	.50	0	2	2	1.5	1.5	.0
3 BENDING								
MACHINE	BEND	.39	0	1	1	1.0	1.0	.O
MANUAL	BEND	5.00	0	2	2	1.5	1.5	.0
4 MARKING	PIECE	.10	15	2	2	1.5	1.5	1.5
5 HANDLING (KITTING)								
STORAGE	PIECE	.10	15	2	2	1.5	1.5	1.5
TRANSPORTING	PIECE	3.00	0	2	2	1.5	1.5	.0
LIFTING	PIECE	5.00	0	2	2	1.5	1.5	.0
6 WELDED JOINTS								
WELDING, BUTT	JOINT	1.70	0	2	2	1.5	1.5	.0
WELDING, SOCKET	JOINT	1.20	14	2	2	1.5	1.5	16.8
7 FIT UP, ASSEMBLE 6 INSTALL								
BUTT	JOINT	1.70	0	2	2	1.5	1.5	.0
SOCKET	JOINT	1.40	14	2	2	1.5	1.5	19.6
FLANGED	JOINT	.80	0	2	2	1.5	1.5	.0
THREADED	JOINT	.50	0	2	2	1.5	1.5	.0
SILBRAZED	JOINT	.32	0	2	2	1.5	1.5	.0
THERMOFIT	JOINT	1.00	0	2	2	1.5	1.5	.0
CRYOFIT	JOINT	1.50	0	2	2	1.5	1.5	.0
MAF	JOINT							
8 SURFACE PREP								
EXTERIOR	SQ FT	.10	0	3	3	2.0	2.0	.0
INTERIOR	SQ FT	.20	0	2	2	1.5	1.5	.0
9 COATING	SQ FT	.20	0	2	2	1.5	1.5	.0
10 INSTALLATION								
PIPE BANGER5	BANGER	.50	0	2	2	1.5	1.5	.0
INSULATION	LN FT	1.14	0	4	4	4.0	4.0	.0
11 TESTING								
AIR	OPENING	.10	0	6	6	7.0	7.0	.0
HYDRO	OPENING	.96	0	6	6	7.0	7.0	.0
AUDIOGRAM	LIN FT	.05	0	1	1	1.0	1.0	.0
x RAYS	LIN FT	.10	0	1	1	1.0	1.0	.0

TOTAL TRADE HANHOURS		44.1
TRADE SUPPORT MANHOURS (35% *OF* TRADE MANHOURS)		15.4
TOTAL PRODUCTION MANHOURS		59.5
LABOR COST (MNHRS X HRLY RATE)	20.00	1190.70
MATERIAL COST (FROM MATERIAL SCHEDULE)		67.10
TOTAL COST		1257.80

DIFFERENTIAL MATERIAL SCHEDULE

ELBOWS, SOCKET WELD, 90 DEG	4 *ea.*	10.76	43.04
ELBOWS, SOCKET WELD, 45 DEG	2 *ea.*	12.03	24.06
TOTAL			67.10

TABLE I - COST ESTIMATING FORM

COST ESTIMATING PROCESS FACTORS MATERIAL: CARBON STEEL
SCHEDULE 40

PIPE SIZE IPS	1 CUT PIPE	2 BEND PIPE	3 (FIT BUTT	4 UP SOCKET	5 ASSEMBLE FLANGE	6 AND THREAD	7 INSTALL) SILBRAZE	8 PIPE INSUL'N	9 HYDRO TEST
.25	.02	.25	.8	.6	.5	.3	.22	.91	.27
.50	.02	.25	1.0	.7	.6	.3	.23	.91	.41
.75	.03	.25	1.1	.8	.6	.4	.24	.91	.55
1.00	.03	.25	1.2	.9	.6	.4	.27	.9l	.68
1.25	.04	.25	1.2	1.1	.7	.4	.28	1.14	.75
1.50	.05	.25	1.5	1.2	.7	.4	.30	1.14	.82
2.00	.05	.39	1.7	1.4	.8	.5	.32	1.14	.96
2.50	.06	.39	1.9	1.6	.8	.5		1.14	1.09
3.00	.06	.39	2.2	1.9	.9			1.23	1.23
3.50	.07	.39	2.5	2.2	1.0			1.33	1.23
4.00	.08	.39	2.7	2.4	1.0			1.41	1.36
5.00	.O8	.39	3.1	2.7	1.0			1.49	1.50
6.00	.09	.39	3.6	3.2	1.1			1.71	1.64
8.00	.15	.72	4.5	4.0	1.1			2.30	1.77
10.00	.21	1.61	5.5	4.9	1.2			2.58	
12.00	.26	4.33	6.4	5.9	1.3			2.84	
14.00	.32	4.33	7.4	6.8	1.4				
16.00	.38	4.33							

SCHEDULE	40	80	160	40	80	160
PIPE SIZE IPS	HELD BUTT	HELD BUTT	WELD BUTT	HELD SOCKET	WELD SOCKET	WELD SOCKET
-25	1.1	1.2	1.4	.7	.8	1.0
.50	1.1	1.2	1.4	.7	.8	1.0
-75	1.1	1.2	1.4	.7	.8	1.0
1.00	1.1	1.2	1.4	.7	.8	1.0
1.25	1.1	1.2	1.4	.8	.8	1.2
1.50	1.1	1.2	1.4	.8	.9	1.2
2.00	1.7	1.8	2.9	1.2	1.3	1.6
2.50	1.7	1.8	2.9			
3.00	1.7	1.8	2.9			
3.50	2.1	2.4	4.2			
4.00	2.1	2.4	4.2			
5.00	2.6	3.0	5.3			
6.00	3.2	3.7	6.5			
8.00	3.9	4.5	7.9			
10.00	4.7	5.4	9.5			
12.00	5.1	6.0	11.0			
14.00	5.9	6.7	12.0			
16.00	6.6	7.8	16.0			

TABLE II - COST ESTIMATING DATA FOR PIPING (P2)

forms is given in Reference (1).

The central portion of all of the forms include the same nine column headings; namely Work Process, Work Units, Process Factor, Unit Amount, Actual Stage, Standard Stage, Actual Factor, Standard Factor and Manhours Required. The data in all but the Unit Amount and Actual Stage columns is protected, so that the information in the protected columns cannot be modified without taking special steps to do so.

Stages. Modern ship construction is based upon modular construction, with each module (or unit, or block, depending upon the nomenclature chosen by a shipyard), passing through a series of stages, each of which is normally associated with specific work sites. While different shipyards may use differing designations and vary the number of stages that they identify, the stages shown in Table III have been selected for use in the CECOP forms. 1 Tab1e 111, the normal location of the work is also shown, to clarify the stage definition and to facilitate the application of this technique to repair work as well as new construction. The column headed Standard Stage identifies the stage at which each work process is most efficiently accomplished, and the stage to which the Process Factors **apply**.

	Stage	Location	Difficulty Factor
1.	Fabrication	In Shop	1.0
2.	Preoutfitting Hot	On Platten- Hot work	1.5
3.	Paint	Paint Shop/Stage	2.0
4.	Preoutfitting Cold	On Platten- Cold Work	3.0
5.	Erection	Erection Site	4.5
6.	Outfitting	Erection Site	
7.	Waterborne	Pierside after Launch	10.0
8.	Tests and Trials	Pierside & Underway	15.0

Table III - Construction Stages and Difficulty Factors

Stage Difficulty Factors. At each stage, a given task becomes progressively more difficult to accomplish than at an earlier stage. Consequently, tasks accomplished later than the standard stage require a greater expenditure of resources. The difficulty factor between stages has been estimated at 1.5 to 2 times the effort required in the prior stage. The work stage difficulty Factors provided in Table III reflect an amalgam of the work stage difficulty data obtained from various sources. Revisions to the work stage factors, based on later and expanded measurements, are anticipated.

When a stage later than the standard stage is entered into the Actual Stage column for a process, the applicable stage difficulty factor is obtained automatically from a lookup table and appears in the Actual Factor column.

Manhours Required. The data in the last column is calculated by the program, by multiplying the process factor by the unit amount and multiplying that product by the ratio of the Actual Factor to the Standard Factor. Values of the ratio of the Actual Factor to the Standard Factor of less than 1.0 are not permitted.

Data Entry

Filling in the form for any CECOP form, then involves only the following steps.

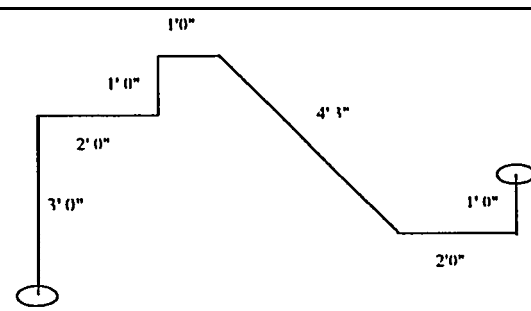
1. Identifying each Work Process which will be involved in the construction of the design alternative being considered and entering, in the Unit Amount column, the number of work units required for that alternative,

2. Entering, in the Actual Stage column, the work stage during which the work is expected to be accomplished. The form already includes the Standard Stage value in this column, making it unnecessary to make any-entry in this column unless the work will be accomplished at some other stage. This column normally will not need to be filled in except after ship construction has started, i.e., for analyses made during the detail design phase.

3. Entering material cost information.

Examples

Pipe fittings vs bending. As an example, the piping cost estimating computer program was applied to two alternative approaches to producing the simple section of piping shown in Figure 1. The differential cost of manufacturing the piping detail by the use of fittings for each change in direction versus by bending the pipe with a pipe bending machine was estimated. The costs of identical material and work processes were ignored and only the costs of the different material and work processes were considered. Table I illustrates the application to the Fittings alternative. The cost differential between the two alternatives was calculated to be $955 in savings for the bending approach.



MATERIAL LIST

		Fittings	Bends
1.	Pipe		
2.	Socket Fig	2	2
3.	Elbow, 90	4	0
4.	Elbow, 45	2	0

Figure 1 - Pipe Example

Schedule slippage. The difference in costs of manufacturing the pipe detail in Figure 1 at different stages in the construction schedule was also estimated, in order to evaluate the effects of late work. In both cases, the pipe detail was assumed to be fabricated with fittings. In the optimum case, the pipe detail is manufactured in the shop, stage 1, and installed in the module at stage 2, Preoutfitting (Hot). In the alternate case, work was not accomplished until the ship is waterborne, undergoing final outfitting. Further, in this case the assumption was made that the pipe would have been cut in the shop, stage 1, but that assembly and welding on board in stage 6 would be required to fit the pipe section into place. This calculation concluded that 107 hours would have been required had the work been accomplished at stage 2, but that 460 hours would have been needed for the same work performed at stage 6. The delay in performing the work would have quadrupled the cost.

Validation

Validation of the CECOP forms and their underlying data tables was attempted by applying them to producibility items that had actually been made by shipyards and comparing the results obtained using CECOP to the results calculated by the yards. Reasonably good correlation was obtained in the several studies that have been made.

However, these attempts demonstrated the difficulty in comparing producibility cost estimates prepared by different organizations. The key problem is determining what is included in the estimate and what functions are omitted. Specifically, many of the work processes considered in the CECOP forms, such as material handling processes, are not normally addressed in shipyard studies. Further, the work process factors used by each group may vary depending on how the factors were developed and the specific processes and equipment available to the yard. Obviously, once two organizations-work together on generating estimates these differences will be highlighted and ultimately eliminated.

Finally, for want of better data, this validation is being made between two estiamtes, without the benefit. of any actual cost data to confirm the accuracy of either estimate. Without the ability to compared estimates against actual return costs for any specific project, the estimating techniques used by either organization are open to question.

Nevertheless, the producibility cost estimates are all that are available and they do provide a tool for decision making. The use of standard cost. estimating computer programs will allow for standardizing the process and permit. the identification of the reasons for differences between the results obtained by diverse organizations.

Validation example 1. A producibility item applicable to handholes and manholes was used. The original method of fabricating handholes, as illustrated by "Current Design" in Figure 2, consisted of welding a 20 mm flat ring to the inside of a 10 mm circular flat bat which was welded into the opening in the deck. Round bar stack with a diameter of 32 mm was cut to 38 mm lengths to form studs. These studs were welded to the underside of the flat ring, drilled and tapped to accept 19 mm (3/4 inch) hold down bolts. The proposed producibility improvement, substituted a 30 mm flat ring for the 10 mm ring. The bolt holes were therefore drilled and tapped into the ring without the installation of the studs.

The shipyard estimated that the old method required 28 manhours per manhole and that the new method would result in a 40% saving in manhours, or 11 manhours. Data was not available to support either the estimate of current manhours or the percentage of savings.

The application of the CECOP structural form to this producibility item gave essentially the same results as the shipyard estimate of the savings.

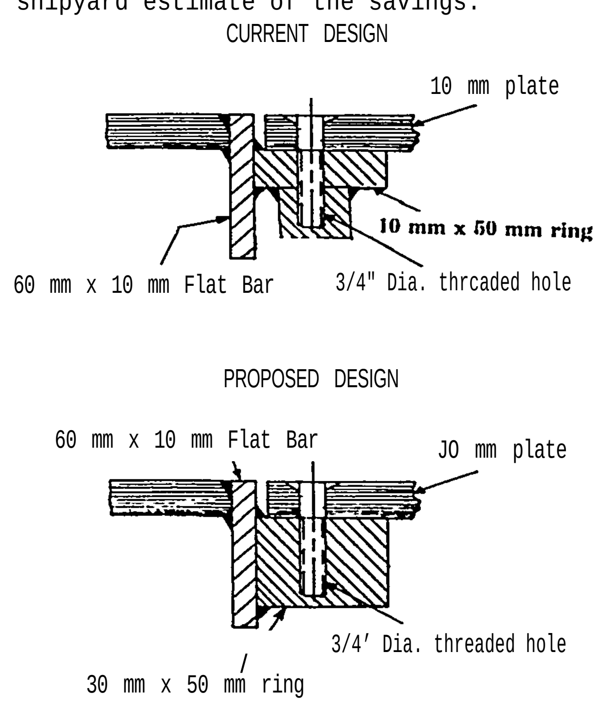


Figure 2 - Manhole Design Alternatives

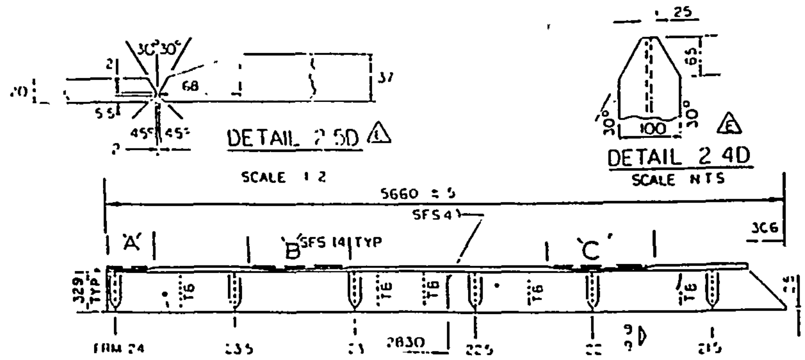


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Figure 3 - Generator Seat Configuration

Validation example 2. A producibility proposal applicable to fabricating Diesel Generator Seats also was used. The original method of fabricating the seats consisted of fitting and welding six sections of plating, alternating in thickness between 20 and 37 mm. The plates were welded together by double sided butt welds, as shown in Figure 3. Each joint required edge preparation with two bevels for each plate. further, the 37 mm thick plate required a longer bevel to reduce the thickness to 20mm at the joint. Overall, each seat was 390 mm wide and 5660 mm long when completed.. The proposed producibility improvement was to use a single 37 mm thick plate and machine the thinner areas to the required 20 mm thickness. The length of the three areas to be machined to 20 mm were 336 mm, 719 mm and 719 mm.

The shipyard estimated the manhour cost savings per seat for machining compared to the use of either manual Shielded Metal Arc Welding (SMAW) procedures or automated Flux Core Arc Welding (FCAW) procedures. Although the shipyard's description of the savings to be obtained included mention of savings in handling and straightening, these savings were not quantified.

The CECOP estimate of the savings to be obtained by use of the modified construction procedures was close to those estimated by the shipyard. Savings in the joint preparation, fitting, welding and cutting were considered. Savings in handling and straightening were omitted, to permit ready comparison with the shipyard analysis. A work stage factor of 1 was applied. A separate sheet of the CECOP form was used for each of the two different material thicknesses and the estimates were added to obtain the final value for each process. The following estimates resulted.

Process	MH FCAW	MH SMAW
Joint prep	1	1
Fit up	4	4
Welding	7	23
Cutting	1	1
Support	5	11
Total Reduction	18	40

In calculating the increase in manhour costs for the proposed method, data for the work process factor for machining were not available, Therefore, the shipyard's manhour estimate for the machining was used to develop a preliminary work process factor for machining. The total machining effort was calculated to be the sum of 16 hours for machining and 5 support hours, for a total estimate of 21 manhours.

Thus, the final CECOP results, showed that the machining approach would result in an increase of 3 manhours over the automatic welding process, but in a saving of 19 manhours over the manual process. These compare with the yard's estimates of a 6 manhour saving over automated welding and 29 manhours over manual welding. These results indicate that the CECOP analysis essentially confirms the shipyard's conclusion that there is little to be gained in changing the current method of fabricating the generator seats when automatic welding is considered. However, there is an appreciable savings to be gained when compared to manually welding the plates. Further, when the savings in shipping, handling and straightening of the welded plates are considered, the savings to be gained from the machined diesel generator seats will increase.

Findings

The correlations achieved in these two validation tests of the CECOP forms demonstrate the potential value of this method in estimating costs of producibility improvement proposals- Future development of the forms and refinement of their backup data should improve the accuracy and reliability of the results which can be obtained.

RELATIVE PRODUCIBILITY EVALUATION

General

The analytical technique described in the previous section requires a significant amount of detailed information about the product and about 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.

However, during the course of this project, the authors found another technique for evaluating the producibility of ship designs to have great value. Although this alternative method provides only a relative comparison of various design alternatives, as opposed to the absolute quantitative valuation described in the-previous section, it may be accomplished when less detailed data are available. This "relative" producibility method may be used as a preliminary test to determine whether to proceed with the "absolute" method.

This second method is an application of the Analytic Hierarchy Process (AHP) developed by Prof. Thomas L. Saaty of the University of Pittsburgh (2). The AHP allows effective decisions to be made concerning complex issues by following several discrete steps.

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 subcriteria 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, as described in more detail later. In accomplishing this step, the intuitive knowledge of experienced individuals is taken into account, as well as the specific information available.

These first two stops need to be accomplished only once at each design stage for any shipbuilding program. Once the controlling producibility criteria and subcriteria have been identified and their relative weighting values determined, they will be used for all evaluations of the producibilty of design alternatives. Thus the development of a specific hierarchy is, at most a one-time effort for each project. It is reasonable to assume that a single hierarchy will be adequate for most shipbuilding programs, since the construction processes in all shipyards arc essentially common.

The third and fourth steps in the process are the only steps that are needed for comparing two or more design alternatives. They involve making a pairwise comparison of each of the design alternatives for each of the subcriteria at the lowest level of the hierarchy and then multiplying these results by the subcriteria weights determined in step 2 and adding up the results. The process will be described by example in later paragraphs.

AHP Advantages

There are several very important advantages to the use of the AHP method. One is that this technique has a rigorous methodological basis. Reference (2) provides further information on this matter. This reference also provides a detailed description of the AHP process as a framework for application to many different areas, including areas not explored by Professor Saaty. However, the examples in the book demonstrate that application of the method to different types of problem requires at least some minimal system engineering effort to structure the problem appropriately.

Another advantage of the AHP is that this process can make use of "hard", numerical data when it is available. For instance, when specific data, such as the length of piping of alternative design configurations, is known, this data may be used directly. But if hard data is not available or if the different attributes that must be considered cannot be measured in common units, this technique is still effective.

Shipbuilding Application

In carrying out the first step of the AHP for shipbuilding program applications, the authors obtained reports from producibility studies that had been carried out on several recent shipbuilding programs. The attributes that were used in each of them for making decisions relative to the selection of preferred design alternatives were compiled. The authors also visiled numerous shipyards to learn about the methods that were used at the yards when making producibility related decisions, with particular attention to the criteria that contributed to their decision making process. Using the data thus obtained, influenced by their own experience, the authors developed a hierarchy of characteristics which control the relative ease of difficulty of constructing the systems of which a ship is comprised.

The parameter tree which has been developed for producibility aspects of a shipbuilding program is described in the following paragraphs. Although this hierarchy has been identified through interviews of personnel at all levels of the design and construction processes, it can be expected that experience with the methodology will lead to additions and or deletions.

Top Level Producibility Criteria

The criteria in the following list were found to be the top level parameters which control the cost of building a ship.

- Arrangements
- Simplicity
- Material
- Standardization
- Fabrication/assembly requirements

AS may be noted from some of these choices, the positive, or most enhancing aspect of the criterion, was selected to dascribe the criterion whenever possible. Thus, Simplicity was used in preference to Complexity. In this way of thinking, the greater value is assigned to the attribute which leads to the least construction effort and cost. This is not always possible when dealing with hard numerical data such as the length of piping or length of welding, but weighting values are appropriately adjusted in such cases.

Underlying Subcriteria

Arrangements. By arranging the structural details of a ship in ways that enhance modular construction breaks, and arranging the equipment within spaces to minimize the length of runs of distributive systems, etc., it is possible to eliminate unnecessary welding, lengths of piping, ventilation ducting, and many other sources of production cost. All of these efforts will result in a reduction of manhours, material cost and construction time, with resultant reduction in recurring construction costs.

Experience has shown (3) that equipment arrangements that were made during the early stages of design often were carried through detail design without any attempt at optimization. When comparing the relative producibility of various design alternatives, the arrangement of structure, equipment and distributive systems can make a major contribution. The next lower tier - the elements which directly affect the producibility of an arrangement - have been identified to be those in the following list.

- Enhanced packaging of components
- Direct routing of distributive systems
- Interference avoidance
- Volumetric density.

Simplicity. The next lower tiers of elements under the primary criterion of Simplicity are as follows.

- Shape of pieces
  - Flat plate
  - Simple curvature
  - Rectangular configuration
- Number of pieces
- Accessibility.

Material/Equipment/Facilities. Use of different types of material, even if more expensive, can lead to fewer construction manhours, (as well as reduced service life maintenance requirements) with net overall reduction in construction cost. No lower tier elements were identified under this criterion during the development of weighting factors far producibility criteria, since it was held that the relative merits of various designs could be adequately evaluated at this level. *However,* should it be found desirable to do so for any specific application, material and equipment costs could be broken down by system type, such as structural, piping, propulsion machinery, etc., and specific facilities to be used or considered could be identified.

Standardization. Use of standard parts, standard processes, etc., has been found to reduce construction costs. Thus it is important to identify the degree of standardization of competing design alternatives when considering their relative producibilities. The lower tier parameters for standardization were established as shown below.

- Component standardization
  - Structural
    - Plate thickness
    - Shapes
    - Sizes
  - Outfitting
  - Equipment
- Process standardization.

Fabrication/Assembly Requirements. The hierarchy of parameters which affect the actual construction processes involved during fabrication and assembly of a ship's equipment and material could be very extensive. The listing which follows is believed to be sufficiently comprehensive to yield valid results for relative producibility evaluations, without being so extensive as to require unnecessary detail in order to carry out the evaluations.

- Welding considerations
  - Process required
    - Automation achievable
    - Position optimization
    - Heat treatment
  - Configuration
    - Weld length
    - Weld type
    - Fillet configuration
      - Plate bevel angles
      - Number of passes

- Sheetmetal considerations
  - Configuration
  - Process required

- Machinery considerations
  - Use of common foundations
  - Mounting details
  - Installation

- Pipefitting considerations
  - Pipe size
  - Length
  - Material type
  - Piping support needs
  - Process
    - Use of bends vs. fittings
    - Connection type

- Electrical/Electronic considerations
  - Wireways
  - Connections/hookups
  - Cable
    - Length
    - Size

- HVAC considerations
  - Ducting
    - Size
    - Length
    - Material
    - Configuration changes
  - Equipment installation
  - Insulation

Weighting Factors

The weighting factors to be used for each of the criteria identified above are obtained by a method of pairwise comparison of each element of a higher level of the hierarchy. Thus, for instance, each of the three first level parameters listed under HVAC (Ducting, Equipment installation, Insulation) would be compared with the other two, and each of the four under "Ducting" would be compared with the other three. 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 very much more important than (actually, 9 times as important as) the other. A questionnaire format has been prepared for accomplishing these comparisons. The format of one element of the questionnaire is shown in Figure 4.

Persons familiar with the influence of the factors identified are asked to circle the numerical value which indicates their considered opinion. A copy of the questionnaire used for developing the data presented in this report is provided in Reference (1). A computer program has been developed to capture the data presented in each questionnaire. The same program can be used for direct entry individual responses to the questions contained in the questionnaire. A second computer program has been developed to combine the results of each individual response into a single weighting factor for each of the parameters of the entire hierarchy. Table IV presents the weighting factors derived from the responses received from those who answered the questionnaire. The values for each series of elements from each level of the hierarchy will add up to 1.0, as can be demonstrated by adding all of the values in Level 1, all of the values for the Arrangement subcriteria of Level 2, etc. The composite figures listed in the last column are obtained from multiplying the factor for each individual subcriterion by the values for each element located above it in the hierarchy. Only those elements of the hierarchy whose composite factors are shown in the column headed "Use" arc used when comparing the producibility Of design alternatives. Again, it is emphasized that this process need be accomplished only once for a specific ship project and design phase. Once the criteria to be evaluated have been determined, and their weighting values calculated, as in the Use column, they are used for evaluating each set of design alternatives.

Evaluating Design Alternatives

In order to determine the relative producibility of two or more competing design proposals, a process similar to that used to determine the performance criteria weighting factors is followed. The difference is that each alternative ship design proposal is compared with each of the other competing design alternatives for each of the lowest tier producibility parameters, again using the 9 to 1 to 9 rating scale. The comparison of the alternative designs can be carried out quite quickly, using questionnaire forms prepared for this purpose. The general format of the questionnaire is as shown in Figure 5.

Several knowledgeable persons should evaluate the same design alternatives. The data from each person's evaluation will be entered into computer programs which will generate a combined *score* for each design for each criterion. The sum of the values for each design is provided by the program. Since these amounts represent relative values and the more producible design is given the

Which of the two parameters below has the greatest influence on construction cost? A 9 indicates very much greater, 7 much greater, 5 moderately greater, 3 somewhat greater, 1 equal influence:

Ducting size .... Ducting Length
9...8....7....6....5....4....3....2....1....2....3....4....5....6....7....8....9

Figure 4 - Pairwise weighting questionnaire element

Which of the two design alternatives has the smaller HVAC DUCTING SIZE, and what is the dogree of difference? A 9 indicates Very much smaller, 7 much smaller, 5 moderately smaller, 3 somewhat smaller, 1 equal:

Alternative A .... Alternative B
9....8....7.... 6 ....5...4...3...2...1..2......3...4...5...6....7...8...9

Figure 5 - Comparison of Design Alternatives for One Criterion

higher score for each criterion, the largest sum will identify the most producible (least costly) design alternative. In order to determine the dollar value of cost savings to be expected, one would then proceed to the "absolute" evaluation described previously.

A simple spreadsheet form, for use when only two alternatives are being compared, is shown in Table V. When evaluating alternative designs using this form, both alternatives are compared for each of the producibility evaluation criteria shown. A value of 1 to 9 is given to the alternative that is more producible, with the value indicating the degree of improvement, exactly as if the scale shown above was being used. The other alternative receives a value of 1.

When hard data is available, it can be entered directly, taking care to enter the data in such a way that the preferred alternative receives the higher value.

Whenever possible, more than two alternative ship design configurations should be compared, since a consistency factor can then be obtained for confidence verification. Thus it is helpful to have information about a baseline ship against which a new ship's basic design characteristics and those of a proposed alternative both may be compared.

Example. In Table V, values reflecting the pipe fitting vs. bend analysis shown in Figure 1 have been entered. Using fittings requires a total of 15 pieces while bending the pipe yields only 3 fittings. To give the higher relative value to Alternative 2, the bending approach, the value of 15 has been entered under Alt. 2 and 3 under Alt. 1. The work to cut the pipe and assemble the joints also will be significantly reduced for the bending case. The ratio of manhours for the two alternatives is estimated to be in the order of 3 to 1. Thus the value of 3 is entered under the Relative Merit column of Alt. 2. As a result of having entered these values, the sum of weighted values for the two design alternatives becomes .4774 for Alternative 1 and .5226 for Alternative 2. Based on the larger value for Alternative 2, it would be concluded that Alternative 2 is the more producible design.

THE DECISION RARING PROCESS

General

Although it is important to know the non-recurring cost of construction of a design alternative, that knowledge in itself is not sufficient to justify a decision to build that alternative. A final decision to approve or disapprove the implementation of any design change involves answering the following questions.

How much will it cost (or save) to implement this change?
How will the schedule be impacted?
What risk is involved?
How will the ship's performance be affected?

Getting good answers to these questions is not simple, but the most difficult task in making the decision is in evaluating the answers, or more correctly, in properly weighting and balancing the answers, since the answers are not normally expressed in comparable units of measures. Because the AHP process is precisely designed to accomplish this type of decision making, the authors proceeded to develop the necessary hierarchy and weighting factores.

	USE	1	2	3	4	5	COMP
		<-----------LEVEL-----------				->	
RECURRING PRS-DELIVERY CONSTRUCTION COST							
Arrangement		.2419					.24190
Enhanced Packaging of Components	.06451		.2667				.06451
Direct Routing of Distributive Systems	.04115		.1701				.04115
Interference Avoidance	.08769		.3625				.08769
Volumetric Density	.04855		.2007				.04855
simplicity		.2239					.22390
Shape of Pieces			.2402				.05378
Flat Plate	.02705			.5030			.02705
simple curvature	.00952			.1770			.00952
Rectangular Configurations	.01721			.3200			.01721
Accessibility	.10714		.4785				.10714
Number Of Pieces	.06298		.2813				.06298
Material	.08000	.0800					.08000
standardization		.2220					.22200
component standardization			.6380				.14164
Structural				.2067			.02928
Plate Thickness	.00709				.2421		.00709
Shapes	.01385				.4732		.01385
Sizes	.00833				.2847		.00833
outfitting	.05106			.3605			.05106
equipment	.06131			.4329			.06131
Process Standardization	.08036		.3620				.08036
Fabrication/Assembly Requirements		.2323					.23230
Welding Considerations			.1271				.02953
Process Required				.5825			.01720
Automation Achieved	.00877				.5099		.00877
Position optimization	.00375				.2179		.00375
Heat Treatment	.00468				.2722		.00468
configuration				.4175			.01233
Fillet Configuration					.3345		.00412
Plate Bevel Angles	.00175					.4243	.00175
Number of Passes	.00237					.5757	.00237
Weld Length	.00326				.2648		.00326
weld Type	.00494				.4007		.00494
Sheetmetal Considerations			.0609				.01415
configuration	.00626			.4427			.00626
Process Required	.00788			.5573			.00788
Machining Considerations			.2118				.04920
use of Common Foundations	.01503			.3054			.01503
Mounting Details	.01440			.2926			.01440
Installation	.01978			.4020			.01978
Pipefitting Considerations			.2057				.04770
Process				.3404			.01627
Use of Bends Vice Fittings	.00902				.5544		.00902
Connection Type	.00725				.4456		.00725
Pipe size	.00627			.1312			.00627
Length	.00615			.1286			.00615
Material Type	.00811			.1698			.00811
Piping Support Needs	.01099			.2300			.01099
Electrical/Electronics Considerations			.2176				.05055
Cable				.2560			.01294
Length	.00641				.4955		.00641
Size	.00653				.5045		.00653
connections/Hookups	.02100			.4154			.02100
Wireways	.01661			.3286			.01661
HVAC Considerations			.1769				.04109
Ducting				.4013			.01649
Size	.00320				.1943		.00320
Length	.00324				.1962		.00324
Material Type	.00291				.1765		.00291
Configuration Changes	.00714				.4330		.00714
Equipment Installation	.01439			.3501			.01439
Insulation	.01022			.2486			.01022
sun of weighting Factors	1.00001	1.0001	4.0000	8.0001	6.0000	1.0000	

TABLE IV - SURVEY WEIGHTING FACTORS FOR PRODUCIBILITY EVALUATION

	REL. MERIT FITTINGS	REL. MERIT BENDS	EVALUATION FACTOR	VALUE FITTINGS	VALUE BENDS
	======	======	I-_-=	e----	s-----e
RECURRING PRE-DELIVERY CONSTRUCTION COST					
Arrangement					
Enhanced Packaging of Components	1	1	.06451	.03225	.03225
Direct Routing of Distributive Systems	1	1	.04115	.02007	.02007
Interference Avoidance	1	1	.08769	.04384	.04384
Volumetric Density	1	1	.04855	.02427	.02427
Simplicity					
Shape of Pieces					
Flat Plate	1	1	.02705	.01353	.01353
Simple Curvature	1	1	.00952	.00476	.00476
Rectangular Configurations	1	1	.01721	.00860	.00860
Accessibility	1	1	.10714	.05357	.05357
Number of Pieces	3	14	.06298	.0llll	.05187
Material	1	1	.08000	.04000	.04000
Standardization					
Component Standardization					
Structural					
Plate Thickness	1	1	.00709	.00354	.00354
Shapes	1	1	.01385	.00693	.00693
Sizes	1	1	.00833	.00417	.00417
Outfitting	1	1	.05106	.02553	.02553
Equipment	1	1	.0613X	.03066	.03066
process Standardization	1	1	.08036	.04018	.04018
Fabrication/Assembly Requirements					
Welding Considerations					
Process Required					
Automation Achieved	1	1	.00877	.00438	.00438
Position Optimization	1	1	.00375	.00187	.00187
Heat Treatment	1	1	.00468	.00234	.00234
Configuration					
Fillet Configuration					
Plate Bevel Augles	1	1	.00175	.00087	.00087
Number of Passes	1	1	.00237	.00119	.00119
Weld Length	1	1	.00326	.00163	.00163
Weld Type	1	1	.00494	.00247	.00247
Sheetmetal Considerations					
Configuration	1	1	.00626	.00313	.00313
Process Required	1	1	.00788	.00394	.00394
Machining Considerations					
Use of Common Foundations	1	1	.01503	.00751	.00751
Mounting Details	1	1	.01440	.00720	.00720
Installation	1	1	.01978	.00989	.00989
Pipefitting Considerations					
Process					
Use of Bends vice Fittings	1	3	.00902	.00226	.00676
Connection Type	1	1	.00725	.00362	.00362
Pipe Size	1	1	.00621	.00313	.00313
Length	1	1	.00615	.00307	.00307
Material Type	1	1	.00811	.00406	.00406
Piping Support Needs	1	1	.01099	.00550	.00550
Electrical/Electronics Considerations					
Cable					
Length	1	1	.00641	.00321	.00321
Size	1	1	.00653	.00326	.00326
Connections/Hookups	1	1	.02100	.01OSO	.01050
Wireways	1	1	.01661	.00831	.00831
HNAC Considerations					
Ducting					
Size	1	1	.00320	.GO160	.00160
Length	1	1	.00324	.00162	.00162
Material Type	1	1	.00291	.00146	.00146
Configuration Changes	1	1	.00714	.00357	.00357
Equipment Installation	1	1	.01439	.00719	.00719
Insulation	1	1	.01022	.00511	.OOSll
		suns:	1.00000	.47740	.52260

TABLE V - PRODUCIBILITY EVALUATION SHEET: TWO DESIGN ALTERNATIVES

Identification of Criteria

Cost, Schedule and Risk. The cost, schedule and risk elements were relatively simple to determine, but performance parameters represented a greater difficulty, since there have been so many prior efforts with significantly different results. The lower level criteria for cost, schedule and risk were selected from those used in several past shipbuilding programs, based on the authors' experience.

Cost Criteria. The cost criteria related to shipbuilding programs are listed below.

- Recurring Predelivery Costs
  - (Producibility)
  - See Table II.
- Nonrecurring Predelivery Costs
  - Program management
  - Design and engineering
  - Production planning
  - Production aids
  - Disruption
  - Delay
- Postdelivery costs
  - Operational costs
  - Consumables
  - Personnel
  - Maintenance
  - Growth/upgrade costs

Schedule Criteria. The following list identifies the lower tier elements of the Schedule criterion.

- Design/Engineering Schedule
- Procurement Schedule
- Construction Schedule

Risk Criteria. The risk criterion is described by the following list of lower tier criteria.

- Maturity of Technology
- Yard Experience
- Degree of development required
- Confidence in Cost estimate
- Confidence in Schedule estimate

Performance Criteria. An initial listing of the lower level elements of a hierarchy of performance criteria was prepared and circulated among numerous individuals who have been directly involved in naval ship design programs, including line officers in requirement setting billets, personnel in ship acquisition program offices and ship design managers. That first listing was revised in response to the comments received and the revised listing was recirculated. Although there was not total agreement, the revised listing was generally accepted. The performance criteria selected are listed below. Certain of these, such as payload carrying capacity, would likely have several lower level tiers, particularly for warships.

- 'Operational capability
  - Payload carrying capacity
  - Payload effectiveness
  - Mobility
    - Speed
    - Endurance
    - Maneuverability
  - Availability
    - Reliability
    - Maintainability
    - Ability to operate in extreme environments
  - Survivability
    - Ability to avoid detection
    - Ability to operate after damage
- Operational efficiency
  - Manning
  - Habitability
  - Safety
- Future growth margin
  - Weight margin
  - KG margin
  - Volume margin (Density)
  - Modularity

Criteria Weighting

Cost, Schedule and Risk. Having established the hierarchy, the next stew in the process was to determine weighting factors for each of the elements in each tier. The cost, schedule and risk criteria were included in a questionnaire similar to that represented by Figure 4, in order to obtain the factors. The results from the questionnaires were fed into computer programs that were developed to analyze the data. Since not all of the individuals who received the questionnaire were asked to identify the ship type or design phase to which their answers referred, the figures provided in Table VI represent an overall weighting for ships in general. The value of 0.0000 is shown for the weighting of test and trials schedule because that criterion was not included in the questionnaires, but was later recognized as a one that should have been included. A copy of the questionnaire used is contained in (1). Copies of the programs used to analyze the data can be obtained from the authors.

Performance. The weighting for the Performance criteria was obtained in a separate questionnaire, distributed at a different time from that for the other criteria. The distribution list. was the same one that was used to develop the Performance hierarchy. The respondents to this questionnaire were asked to identify the ship class and design phase to which their answers were applicable. Since virtually all of the respondents were involved in the early stages of the

	USE	LEVEL 1	LEVEL 2	LEVEL 3	COMB
1. COST		.I731			.I7310
1.1 Recurring Predelivery Construction Cost			.3334		.05771
1 .2 Non-Recurring costs; predelivez			.3333		.05769
1.2.1 Design and Engineering	.04327			.7500	.04327
1.2.2 Production Planning	.00577			.1000	.00577
1.2.3 Production Aids/ Tooling	.00288			. OS00	.00288
1.2.4 Disruption	.00288			.0500	.00288
1.2.5 Delay	.00288			.0500	.00288
1.3 Postdelivery Costs			.3333		.05769
1.3.1 Operational Costs	.01442			.2500	.01442
1.3.2 Coneumables	.01442			.2500	.01442
1.3.3 Personnel	.01442			.2500	.01442
1.3.4 Maintenance	.01442			.2500	.01442
2. SCHEDULE CRITERIA		.1076			.10760
2.1 Design/ Engineering Schedule	.03159		.2936		.03159
2.2 Equipment/Material Procurement Schedule	.02369		.2202		.02369
2.3 Construction Schedule	.05232		.4862		.05232
2.4 Test and Trials Schedule	.00000		.0000		.00000
3. RISK CRITERIA		.3200			.32000
3.1 Naturity of Technology	.12867		.4021		.12867
3.2 Yard Experience	.09539		.2981		.09539
3.3 Confidence in Cost Estimate	.5114		.1598		.05114
5.4 confiqence in schedule Estimat	.04400		.1400		.4480
1 PERFORMANCE CRITER1A	.39940	.3994			.35940

Table VI SURVEY WEIGHTING FACTORS

ship design process, (when performance variation tradeoffs may still be made) the results are most representative of those phases. Table VII provides the results of this effort. Values were obtained for aircraft carriers (CVN), Destroyer/Cruisers (DD), Frigates (FFG), Small Combatants and Amphibious ships. Some of the respondents considered their response as being good for any ship. Their responses, plus the responses in which no specific ship class was identified, are included in the listing for "Any" ship. The column headed NGM5 contains the. normalized geometric mean of the values given in the first 5 columns. The column headed NGM6 includes the values in the "Any" column as well.

Application

Once the hierarchy that is appropriate to the ship type has been established, and the weighting factors have been determined, the choice between competing design alternatives becomes a matter of evaluating each alternative against each criterion in the hierarchy and selecting the alternative which achieves the highest overall weighting factor. In most cases, there will be relatively few criteria that actually are involved, and the process will be very simple.

Despite the fact that it is preferable to have more than two alternatives to evaluate simultaneously, it is most likely that only two will exist. Simple spreadsheet forms have been developed for comparing two or three alternative designs (1). It would be simple to generate similar forms for evaluating additional alternatives simultaneously. Table VIII illustrates the use of the form for evaluating two alternatives, as applied to the decision to use pipe fittings or to bend the pipe shown in Figure 1.

Although the pipe bending approach was identified as the more producible, the other criteria which control the decision making process must be considered. The lactors for recurring cost are taken from the results of the producibility evaluation, Table V.

The non-recurring cost of producing drawings and equipment lists will be somewhat greater for the fittings case. Assuming that the design and engineering effort will be about 50% greater for the fittings case, a superiority factor of 1.5 is assigned to that criterion. Normally this value would have been entered into the separate computer program that has been prepared for this purpose. The program would have generated a value of

SHIP PERFORMANCE CRITERIA	CVN	DD	FFG	SHALL COMBATANT	AMPHIB	NGM5	ANY	NGM6
operational capability	.7009	.5971	.4947	.3326	.2326	.5205	.6074	.5399
Operational Efficiency	.2020	.2106	.3808	.5278	.0543	.2564	.3033	.2665
future Growth Margin	.0971	.1924	.1246	.1396	.7131	.2231	.0893	.1936
Operational Capability								
Payload Carrying Capacity	.0666	.1293	.0971	.2093	.0563	.1057	.1252	.1095
Payload EffectiVeness	.3252	.3030	.3090	.2474	.3021	.3138	.3509	.3222
mobility	.0362	.1194	.1178	.1629	.0373	.0838	.0766	.0832
Availability	.1814	.2516	.3483	.2460	.3021	.2752	.3404	.287;
survivability	.3907	.1967	.1279	.1344	.3021	.2215	.1069	.1977
Mobility								
speed	.4444	.3174	.2444	.4891	.2326	.3468	.2120	.3216
Endurance	.4444	.5110	.5070	.3296	.7131	.5103	.6280	.5318
Maneuverability	.1111	.1716	.2486	.1813	.0543	.1429	.1600	.1466
Availability								
Reliability	.6047	.5508	.5677	.3041	.5589	.5570	.5082	.5495
Maintainability	.1047	.1393	.2377	.1206	.3829	.1929	.2583	.2029
Ability/Environm Extremes	.2906	.3099	.1946	.5753	.0582	.2501	.2334	.2477
Survivability								
Ability/Avoid Detection	.2743	.7306	.6667	.7388	.5000	.5870	.4654	.5671
Ability/Operats Damaged	.7257	.2694	.3333	.2612	.5000	.4130	.5346	.4329
Operational Efficiency								
manning	.7142	.3768	.4396	.6042	.4040	.5220	.3479	.4929
Rabitability	.1429	.2066	.1118	.0729	.0687	.1173	.1083	.1169
Safety	.1429	.4166	.4486	.3229	.5273	.3607	.5439	.3902
Future Growth Margin								
Weight Margin	.3214	.2460	.1824	.2557	.0763	.2184	.1852	.2151
KG Margin	.3214	.1582	.4206	.2733	.6097	.3628	.2995	.3558
volume Margin (Density)	.3214	.2060	.2157	.2292	.1294	.2370	.1501	.2223
Modularity	.0357	.3898	.1813	.2417	.1846	.1818	.3652	.2068

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TABLE VII - PERFORMANCE CRITERIA WEIGHTING FACTORS BY SHIP TYPE

.4000 for fittings and .6000 for bends. The results for the final weight columns would have been identical. The information *is* presented as it *is in* Table VIII to demonstrate the flexibility of the technique which has been developed.

Because the production engineering effort would be slightly greater for the fittings case, a superiority factor of 1.1 has been entered in the pipe bending column.

These values for non-recurring costs have been based on the assumption of a one time application. In a real situation, the non-recurring cost for each alternative may be increased by the number of applications per ship, resulting in a greater total non-recurring cost differential. The non-recurring costs may be applied over more than one ship, in which case the relative superiority of one design alternative to another would need to be reduced accordingly.

Under service life costs, since more joints exist in the fitting method, it is more likely that a maintenance problem will occur during the operational life of the ship. On the assumption that maintenance costs for fittings will be twice those for the bent pipe, a superiority factor of 2 was assigned to the latter.

It should be noted that if cost estimates had been prepared for any of the cost-related criteria, those "hard" numbers could have been substituted in place of the relative values that have been used.

The choice of either bends or fittings is not likely to have any notable effect upon schedule, risk or performance, no changes were made to the table, thus, in effect, treating the two design approaches as being equal with respect to these criteria.

With these data entered into the form, the overall values for Fittings and Bending, shown at the bottom of the Final Weights columns *on* the form in Table VIII, become .4914 and .5086, respectively. This result demonstrates that the bending choice is the preferred alternative from the overall perspective as well as from the standpoint of producibility alone.

CRITERIA	WEIGHTING FACTOR	SUPERIORITY FACTORS PIPE FITTINGS	SUPERIORITY FACTORS PIPE BENDING	FINAL WEIGHTS PIPE FITTINGS	FINAL WEIGHTS PIPE BENDING
COST					
Recurring Cost (Producibility)	.0577	.4774	.5226	.0275	.0301
Non-Recurring Pre-Delivery Cost					
Design and Eugineering	.0293	1.0000	1.5000	.0117	.0176
Production Planning	.0163	1.0000	1.1000	.0078	.0085
Production Aids/Tooling	.002.,	.5000	.5000	.0012	.0012
Disruption	.0042	.5000	.5000	.0021	.0021
Delay	.0055	.5000	.5000	.0028	.0028
Service Life Cost					
Personnel	.0150	.5000	.5000	.0075	.0075
Consumables	.0189	.5000	.5000	.0094	.0094
Maintenance	.0238	1.0000	2.0000	.0079	.0159
SCHEDULE					
Design/Engineering Schedule	.02?7	.5000	.5000	.0149	.0149
Rquipment/Material Procurement Sched	.0218	.5000	.5000	.0109	.0109
construction Schedule	.0504	.5000	.5000	.0252	.0252
Test and Trials Schedule	.0056	.5000	.5000	.0028	.0028
RISK					
Maturity of Technology	.1287	.5000	.5000	.0643	.0643
Yard Experience	.0954	.5000	.5000	.0477	.0477
cost Estimate Confidence	.0511	.5000	.5000	.0256	.0256
Schedule Estimate Confidence	.0448	.5000	.5000	.0224	.0224
PERFORMANCE	.3994	.5000	.5000	.1997	.1997
	1.0000			.4914	.5086

TABLE VIII - DESIGN SELECTION CALCULATION SHEET

CONCLUSIONS

The authors consider that the methods presented herein are logical, straiqhtforward and easy to use. The validation tests have yielded results that are consistent with the findings of the shipyards from which the design-alternatives were obtained. While the quantitative data has not been sufficiently tested to conclusively prove the degree of accuracy which the data provides, it is considered to be of at least first order accuracy. Requests from shipyards for comments on the values used have not yielded any negative responses.

The techniques have been used only on rather elemental evaluations to date. Their application to these has proven very easy to accomplish, and the results have been apparently accurate. Although an application of either technique to a large scale ship design alternative has not yet been tried, it is expected that the larger scale problems will be found to be made up of numerous elements, each of which can be treated with the techniques presented herein.

A familiarity with ship production processes is certainly helpful when using the CECOP programs, but the questions that. must be answered are explicitly stated on the forms. It seems apparent that even a novice user would quickly gain familiarity with the information needed to fill in the forms, and thus that the forms will be useful to designers and managers involved with early design stage decision making as well as during the detail design process.

The authors have found that there are individuals in most organizations who have at least some degree of familiarity with the AHP method. The computer programs that accompany (1) will allow the necessary calculations to be made at any desk top-or laptop computer. Should any questions arise in applying these techniques to specific shipbuilding, overhaul or repair projects, it will be easy to find sources of solutions.

ACKNOWLEDGEMENTS

The authors are indebted to Mr. and Mrs. Kenneth Borchers for their initial development of the questionnaires used to perform the pairwise comparisons,from which the weighting factors are obtained, and for the initial development of the Basic programs used for evaluating the results from the questionnaires. The support and participation of each of the shipyards which provided producibility study data for evaluating the methods proposed are also acknowledged, with particular thanks to Ingalls Shipbuilding Division, Bath Iron Works and Saint John Shipbuilding Ltd. Finally, the authors wish to express great appreciation to the many individuals in shipyards, NavSea, SupShips offices, SP-4 and elsewhere, who answered the questionnaires, and provided suggestions and guidance during the course of this effort.

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