

**THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS**  
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Paper presented at the 1998 Society of Naval Architects and Marine Engineers Annual Meeting  
November 11-14, 1998 San Diego Concourse, San Diego, California  
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## **Keys To CAD/CAM In Small Shipyards**

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### **ABSTRACT**

*Many small shipbuilders use Computer Aided Lofting/Numerically Controlled Cutting (CAL/NCC) to automate lofting and shipfitting and have reduced costs, but CAL/NCC is only the beginning in a journey of continuous improvement. Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) is much more than a series of unrelated methods to automate specific tasks - it is a primary enabling technology because it is a fundamentally different paradigm for documentation of design and communication throughout the shipyard. Proper implementation of CAD/CAM will reduce costs by enabling other techniques and processes, but this requires many radical changes in process and paradigms throughout the shipbuilding process. There are eight keys in the chain to improved productivity: Process re-engineering, the integrated product model, design for NCC production, advanced outfitting/group technology, a flexible standard product line, concurrent engineering, advanced workflow control and statistical process measurement and control. Each of these keys enables each other and is enabled by CAD/CAM. However, each shipyard must approach this technology based on their resources, processes and customers and will therefore implement these processes differently. The authors discuss each key concept, provide case histories, and propose methods and suggestions for deciding how, how much, when and if to implement each of these keys.*

### **INTRODUCTION**

Computer-Aided-Design/Computer-Aided-Manufacturing is a new paradigm in ship design and construction. CAD/CAM represents a sea change in the role of the naval architect and in fact the entire process of shipbuilding. It blurs the traditional lines between design and production, offers new opportunities for productivity improvements through automation and can improve both productivity and life cycle management. For example, Computer Aided Lofting/Numerically Controlled Cutting (CAL/NCC) involves fitting steel at the keyboard rather than in the shipyard. CAD/CAM involves technical problems, but in any case, human, organizational and management issues produce the most important challenges and the greatest opportunity for improvement. Numerous small shipyards have been able to implement various aspects of CAD/CAM and derive great benefit

from it. Each shipyard has differed in the exact details of their approach but all of them ultimately realize that this is a continuous process of improvement.

While the entire shipbuilding industry, from the small boatyards to the big six shipyards, continues to improve, the approach to the use of CAD/CAM tools is different. The large shipyards typically tackle their process analysis and improvements with large-scale systems. The smaller yards must use simpler approaches.

CAD can be viewed as just a new means of communication and information storage, but it adds versatility and richness to information. Digital data differs from earlier forms of information storage because it is more readily transferable from one form to another, such as CAD files to CNC code that can drive automated machinery. Digital data can also be readily linked to an increasingly diverse range of other data including links through the Internet to data stored on the other side of the

world.

Communication, and information handling and generation are functions of management and engineering, so the challenge of CAD/CAM is primarily a challenge to managers and engineers. There are numerous vendors of technical solutions and virtually any software problem can be, or more likely has been, solved. The challenge is to select appropriate solutions and to find opportunities for improvements throughout the shipbuilding process.

Providing a manual for implementing and optimizing the use of CAD/CAM is impractical. Not only is space limited, but the needs and capabilities of each shipyard differ. Software and hardware capabilities also change on a daily basis. Our goal is to point out opportunities and problems and suggest processes for each shipyard to tailor CAD/CAM to their needs.

We have identified eight keys to making the most of CAD/CAM. Together they form a circular process:

- **Process re-engineering** systematically examines the needs and capabilities of all members of the organization, and looks for opportunities to change for improvement, not only in particular processes, but in the interaction of processes. CAD/CAM improves communications between processes as well as allowing improvements within processes.
- **The integrated product model** is the central reservoir of information on the ship. CAD/CAM enables construction of the product model, while process re-engineering develops the conventions of, and type of, information in the product model.
- **Design for NCC** includes incorporating features to improve productivity, and modifying structural design to take advantage of automatic cutting. The product model is used to develop NCC data and process re-engineering is required to develop these changes so that they meet the needs of production.
- **Advanced outfitting/group technology** is installing machinery and other outfit as early as possible, and classifying and organizing tasks by location and type of processes/problems to accomplish installation as easily as possible. Process re-engineering develops these processes and ensures that other processes feed the right parts and information to them. The product model and NCC ensures that the geometry of the structure is accurate and allows better planning.
- **A flexible standard product line** is building different ships (or other products) by using standardized systems, preferably with parameterized details and standard components and thus predictable work, cost and process content. CAD automates and documents the use of standardized products.
- **Concurrent engineering** is doing design simultaneously across disciplines and includes all aspects of production as well as the final product. The product model is the essential communications

tool for concurrent engineering, and process re-engineering assures that production concerns are addressed from the start.

- **Advanced workflow control** is a variety of techniques to schedule, predict and control work packages, thereby increasing productivity. These techniques depend on the product model for information on sequencing, and on group technology for resource allocation, cost, and schedule prediction.
- **Statistical process measurement and control** is the measurement and application of statistics to the results of all the other processes and changes. It provides feedback to improve schedule and cost reliability and guide further process re-engineering. This closes the circle of continuous improvement.

By small shipyards, the authors primarily mean “second tier” or “third tier” shipyards, which often build ships for coastal or shallow water, hence the term “brown water” shipyards. Several criteria are of relevant for this discussion:

- Small shipyards use adaptations of general-purpose CAD systems with varying combinations of special software rather than dedicated, usually mainframe or workstation based systems, for shipbuilding.
- Small ships are designed and built over a relatively short period of months instead of years, with correspondingly short equipment lead times.
- Small ships are often produced in series, and even if not part of a class tend to be very similar in detail within a given shipyard.
- Small ships also tend to have a majority of complex structural shapes with little repetition: They rarely have significant parallel midbody or large flat panels.
- These ships are usually built by shipyards with much fewer than a thousand employees and hence have substantial limits on the resources they can apply to use of new technology.

*“That went about as well as could be expected”*

*Wallace, A Close Shave*

The authors’ experience is based on a large number of projects in a range of shipyards, but two small yard occasions provided much of the experience:

Munson Manufacturing is a small shipyard building aluminum workboats in the Pacific Northwest with a few dozen employees. CAD/CAM implementation began at Munson in 1991-1992. During this period, some 36 boats ranging from 20 to 55 feet long were built with an increasing proportion of metal for each succeeding boat numerically cut. No formal processes or plans were used to implement CAD/CAM, but in such a small shipyard, there was extensive informal employee involvement at all levels.

The Coast Guard YARD in Curtis Bay MD was awarded, in 1996, a contract to build the first five small steel stern loading buoy tenders of a potential 34. The BUSLs (Boat, Utility, Stern Loading) are 49 feet long with twin engines, short term accommodations for a crew of four and a stern hydraulic a-frame with associated winches for handling buoys up to 4,500 pounds. This was the first major construction project in some years. The YARD is ISO 9001 certified (the first public shipyard to be certified), so a formal documentation of all processes affecting quality was required. Therefore, a major, formal effort was made to reorganize steel production using CAD/CAM, as a first step in implementation of an integrated CAD/CAM system. Virtually all of the steel for all the boats was numerically cut from the beginning.

These two experiences occurred in almost polar opposite with regard to size, level of organization, type of boats and virtually every other feature. However, the successes and problems in two so opposite environments were remarkably consistent.

Finally, the authors' experience principally involves AutoCAD and related AutoDesk compatible products. This includes ShipCAM, a specialized lofting and fairing system developed by one of the authors. Hence, this account addresses use of AutoCAD and ShipCAM when it is necessary discuss specific techniques. AutoCAD is probably the most prevalent CAD design tool in use at small shipyards, but there are other excellent CAD and lofting products. There are also arguments of near religious intensity between the proponents of the various systems. The authors' emphasis on AutoCAD and ShipCAM is a record of our experience and not intended to be a claim that these products are the only or even the best ones for shipbuilding. We especially welcome comments and insight from users of other systems.

## **PROCESS RE-ENGINEERING FOR INTEGRATED CAD/CAM**

*"Engineers and Designers Need to Gain Profound Knowledge of the Erection Process and Incorporate Product Design and Process Design Producibility Features into the Detail Design."*

### **Deming**

Shipyards throughout the world have introduced various aspects of CAD/CAM piecemeal as substitutes for manual processes; however, the greatest improvements in shipbuilding are achieved by improving the interfaces. Design, production, planning, weight control, procurement, and logistics support must be combined in a new integrated environment where the same "keystrokes" that create the preliminary design are used through the entire shipbuilding process.

Re-engineering underlies all other efforts, because all

yard processes should be changed to make the best of the richer, more versatile information available from CAD. Re-engineering requires documented "profound knowledge" of all processes, team building and an organized process for continuous improvement.

Technology advances should promote cross-functional process improvement rather than just automating existing tasks. The typical approach to implementing technology in many manufacturing organizations consists of little more than simply automating existing task structures. Assessing the impact of technology as an integrated system is the basis of process re-engineering and large-scale improvement.

The authors intentionally use CAD as an acronym for Computer Aided Design rather than Computer Aided Drafting. Viewing CAD as just a drafting tool - a sort of electric pencil - and the paper drawings as an end product rather than an interim product is perhaps the single most limiting paradigm that has hindered productivity gains from CAD.

The failure to realize significant productivity gains due to computer applications has been noted in many industries, especially architecture [Dakan, 1994]. When the computer is compared with other earlier technological developments, such as the steam engine, comparable gains in productivity have not been seen. The authors contend this is because the real gains in productivity were not seen until the entire system changed - for example, in the British Isles, railroads increased productivity in industrialization when food production became distant from industrial production, and the crops grown, and hence worker's diets, shifted to potatoes. (That this systemic change had disastrous consequences later is another lesson we should perhaps heed as well.) The requirement for changes throughout a manufacturing process due to an improvement in any part is obvious from the historic perspective.

The goal of the designer should be to produce information promoting optimally efficient production. Ship's drawings are an interim product as well as an end product. They must be optimized for production added value and possible adaptation or replacement just like everything else in the shipbuilding process.

Implementing this new paradigm requires an organized approach using a systemic management approach (a holistic view of all the shipyard's processes as one system), and process re-engineering as a tool within the context of the systemic approach.

The authors have had the opportunity to witness process improvement efforts through new technology deployment at a number of shipyards and manufacturing organizations. When new technology fails to reap significant real productivity improvements, the reason is usually the same: many shipyards try to implement new technology by simply automating existing processes.

This usually results in workers making the mistakes they have always made, producing the same rework they have always produced, and failing to meet the same requirements they have always failed to meet, except with new technology they simply do it faster. Even in the best cases, automating existing processes only produces savings in the specific process automated. Often any improvements resulting from automation are offset by the cost, labor and training needed to implement the new technology. The common result is the production of products and services lacking in the features, functions and outcomes desired by those downstream in the process. This is especially tragic when this scenario occurs in the detail design phase of the ship building process. The real cost savings derived from integrating CAD/CAM are in the process design: The design group giving the production shops exactly what they need in the format they need, when they need it. The emphasis, even from the end customer buying the product, is quite often on efficient product design. This emphasis is misplaced, because the key to success in manufacturing efficiency is in marrying the product design (the actual design features of the boat) with process design (how the boat is built).

It is worth considering the conventional process for CAL/NCC in small shipyards and looking at the lost productivity:

- The designer develops a set of lines in two dimensions using a PC fairing program, and gives a paper drawing to the loft (or a lofting service).
- The designer develops 2D structural drawings using the data from the original lines in CAD. (In general not all parts are drawn, only “typical” ones.)
- The designer develops 2D orthographic drawings of other systems using the structural drawings and lines drawing.
- The lines are re-faired by the loft from the paper lines drawing - the hull shape changes slightly.
- The loft extracts molded lines from the faired hull shape where structure is required.
- The loft lays out the structural details in the molded lines, by modifying structural details as required based on their knowledge as shipfitters and the customary details used in the shop. These details rarely make it back into the design details because of limited engineering budgets and traditional boundaries between production and engineering.
- The loft converts the structural details into code to drive a Computer Numerically Controlled Torch.
- The cutter operator makes parts.
- The shop erects the parts using the drawings from the designer and the parts from the shop, making errors because the drawings don’t quite match the parts and because the information is presented in a fashion the designer wants, not the way the shop needs it.

This process unfortunately, is more common than not. It is essentially the same process as would be done by hand, but with a few steps done on a computer. This results in some improvement by automating specific steps but little overall gain is realized. The most obvious loss is that the lines and structural details are drawn twice. A subtler problem is that the exact geometry of both the hull and structure changes slightly so that the fit of machinery, piping, and joiner-work is not exact, making prefabrication outside of the finished structure difficult. The designer also almost certainly will not design the ship in the way the shop wants to build it.

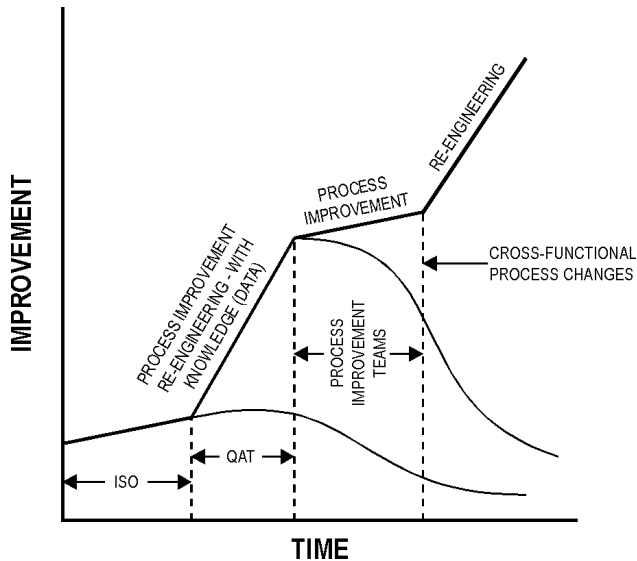
Finally, the drawings never exactly duplicate the ship, which may require an extensive rework of the drawings, or loss of configuration control so that the ship is never quite as easily maintained throughout its lifecycle.

Even presentation is an important issue, with great opportunities for improvements. Two examples illustrate the shift in paradigm due to CAD (and lessons for one of the authors):

- Hand drafting standards prohibit showing a dimension that can be independently derived from another group of dimensions in the drawing set (so-called “double dimensioning”). However, such non-redundant dimensions are difficult to find in the shop and require that workers make calculations to get the dimension they need to lay out a component. CAD data from a product model is exact and consistent and CAD uses automatic associative dimensioning to minimize errors. Double dimensioning is perfectly acceptable in CAD and will save labor and rework in production.
- Perspective or isometric drawings enable workers to better understand and plan their work than conventional drawings and can be easily produced from a product model. Sketches of formed plates are especially valuable for avoiding errors and fabrication rework. All types of three-dimensional drawings are readily derived from a product model.

## **NO PROCESS IS AN ISLAND**

The first corollary of Deming’s Theory of Profound Knowledge is that if management is going to improve its organization it must gain profound knowledge of the processes and systems which comprise the organization. Processes like CAD/CAM require an even more comprehensive understanding than most processes, since this process more than any other has the ability to affect almost every core ship and boat building process in a shipyard. Yet the CAD/CAM process involves a degree of technology that can be challenging to explain to upper management and non-technical personnel.



**Figure 1**  
**Process Improvement**

### THE CONTINUOUS PROCESS IMPROVEMENT MODEL

Figure 1 illustrates the basic approach used for implementing process improvement. The quality documentation or “ISO” phase involves documenting the process and getting rid of the “obvious” waste. The Quality Action Teaming (QAT) phase involves establishing basic guidance and making decisions about what needs to be improved. Issues such as what needs to be done, who needs to do it, and upper management authorization and support for the changes are established at this phase. Process Improvement Teaming involves actually implementing the changes, working out the details of making the process changes work and then measuring the results to determine if the implemented changes actually improved the process. Once this phase is accomplished, the stage is set to actually re-engineer the process.

Organizations fail at process re-engineering by going directly from ground zero to the process re-engineering phase without taking time to develop profound knowledge of what they are trying to improve. This knowledge comes from first documenting the process and second (and most important) trying to improve the process. According to Deming, nothing provides as much knowledge about a process as trying to improve it. This is the theory of continuous improvement: The very act of trying to improve a process will precipitate the development of profound knowledge about the process. The risks accompanying process re-engineering (involving massive process change), are mitigated. However, when organizations try to re-engineer processes that are barely even documented, disastrous consequences

usually result and the re-engineering effort degenerates to little more than a very poorly planned reorganization.

The curves in Figure 1 indicate that at each phase of the improvement cycle, if the commitment to continuous improvement is lost, the process invariably reverts to its initial condition. This subtle aspect of continuous improvement is emphasized by the fact that shipyards that do not maintain a commitment to continuous improvement actually look like they are moving backwards when compared to shipyards that have institutionalized this principle.

Continuous improvement with CAD/CAM requires that the shipyard department responsible for generating CAD/CAM data, the “process owner”, gain profound knowledge of the downstream processes, especially for closely tied processes like cutting and assembly. Even determining the process owner may be an issue, since it is cross-functional between design and production. Such steps as merging the traditional loft and the traditional structural design functions may be worthwhile. There is even some merit to merging design and production functions by product. The steel production process might be vertically integrated by merging structural design, the loft and steel trades into a structural production group, and machinery design, machine shops and piping into a machinery production group, and so on. Previously, coordinating information between these groups would have been very difficult, but the product model is a powerful tool for maintaining a consistent database and facilitating coordination.

Detail design drawings must incorporate both product and process features, which are now made available by the highly accurate electronic information. Traditionally, the mindset is that production has the responsibility to ask for what they need. Even a concurrent engineering (CE) approach does not address fully the CAD/CAM producibility issues, since CE focuses primarily on product design. However, production has no way of knowing the process design impact of numerical lofting capabilities and what design can provide to make the fabrication and erection more efficient. Rather, it is incumbent upon design (or those upstream in the process flow) to determine the needs and requirements of those downstream in the process. This is easier said than done, especially when the production floor may not be able to articulate the desired design features and functions in a way that is meaningful for the design effort. The process owner must lead the effort in:

- Gaining a clear understanding of every aspect of the fabrication process
- Obtaining from production personnel exactly what design aspects will promote efficient fabrication

### ISO-9001 and the Baldrige Quality System

The ISO-9001 Quality Standard, which emphasizes

process control, is a big boost to achieving success in process re-engineering because of the discipline that ISO-9001 invokes. ISO-9001 (ISO) requires detailing out each step of the process (for critical steps, right down to the keystroke) and building consensus among the functional elements, such as the design functions and the production shops. Since one advantage of CAD/CAM involves blurring the lines of distinction between design, lofting and production, solid technical communication is essential to assure the requirements and potential efficiencies of each work unit are fully addressed.

ISO requires a level of process documentation and control that helps create a process focus. Therefore, as this technology continues to advance, the value and potential benefit of an ISO style process management system will increase. ISO provides the framework that is needed to successfully focus on the cross-functional impact of the CAD/CAM technology. Much of the benefits of integrated CAD/CAM lies in the production of templates, fiduciary markings which eliminate measuring on the shop floor, improved fabrication shortcuts and by reducing the number of times a boat is redrawn by the various interim users of the geometry. All of this requires carefully coordinating the detail design with production because shipfitting is done electronically on the computer “lofting floor” instead of on the production floor.

One note of warning regarding ISO: Shipyards that seek to obtain ISO certification as an end in itself are most likely missing these benefits. The real benefits of ISO are only achieved when ISO is coupled with a policy of continuous improvement. ISO degenerates to little more than a paper chase for organizations that do not pursue continuous process improvement coupled with ISO as a means to institutionalize continuous improvement, rather than an end in itself. ISO probably is a waste of money for organizations that do not have a policy of continuous improvement. The real benefit of ISO is that it provides the beginning point of real process management that involves both process control and process improvement. Documenting processes is an expensive and time-consuming undertaking and little worth the effort if nothing will be done with this mountain of paper resulting from process documentation.

The YARD, like most all traditionally structured shipyards, has a job shop structure. The organization is broken into shops organized along disciplines, such as inside machine shop, outside machine shop, welding shop, engineering hull branch, engineering machinery branch, etc. A weakness of this type of organizational structure is that it tends to create myopia among functional managers wherein self concern and turf protection become more important than efficiently accomplishing the work from an overall project perspective. ISO can help serve as the initial beachhead to address this sub-optimizing mindset, since it requires

as a minimum that cross-functional processes, called Management Operating Procedures and Discipline Specific Operating Procedures be documented. The mere act of documenting important processes adds a great deal of understanding and brings into the open some obvious inefficiencies that were not obvious before the processes were documented. Most important, ISO can provide a springboard to create a process improvement system.

The YARD ISO Quality System provided the foundation and requirement to develop and successfully deploy the detailed process steps. In order to implement the Integrated CAD/CAM process, several quality technology tools were used. Initially, a scaled-down version of the Quality Function Deployment (QFD) planning method was used. The QFD approach provided the context to define the required features, functions and outcomes of each CAD/CAM product, such as fully lofted, true geometry detail design drawings, and interim products, such as roll sets, construction templates, and fiduciaries.

The YARD also used the Malcolm Baldrige National Quality Award (MBNQA) Criteria. This criteria provides the framework for a performance-based management system, meaning the Baldrige is a management system that is based on measurement, with all elements connected to the strategic objectives of the organization through a system of credit and accountability. The Baldrige criteria heavily emphasize using systemic, systematic approaches to achieve success in key indicators of tactical and strategic results.

Systematic process improvement proceeds in these steps:

#### Documentation

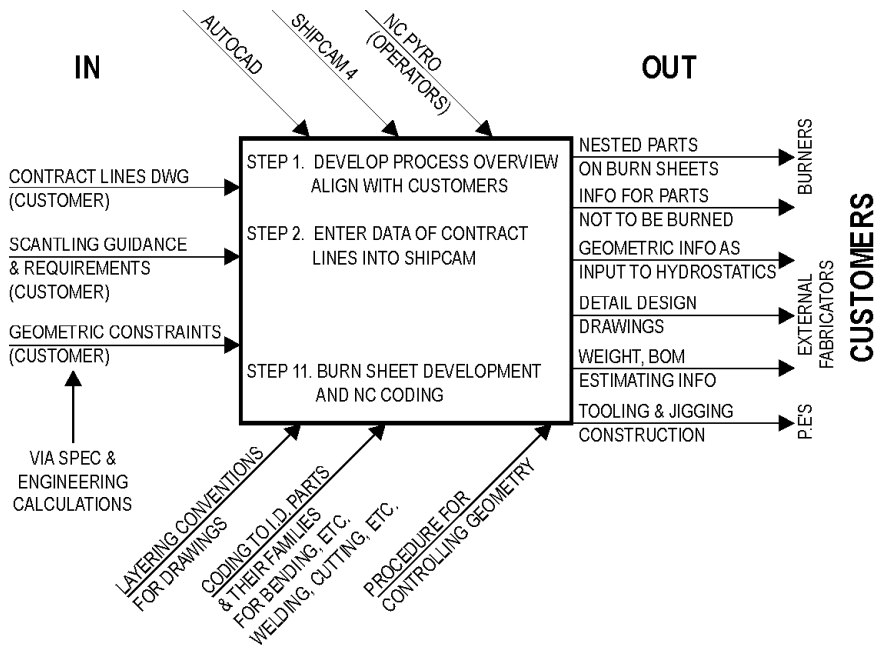
Document the process as it currently operates (without fully integrated CAD/CAM). Include related processes such as weight management and procurement document (bills of materials) development. If you don't know where you are, it is difficult to know which way to go.

#### Benchmarking

Find out how leading shipyards and engineering design groups perform integrated CAD/CAM. Identify the industry leaders in this process by using competitive comparison measurements, such as labor hours per ton of lofted steel and the level of integration of the detail design and numerical lofting processes with other processes.

However, design process “metrics” are very difficult to determine and implement. A good discussion of design metrics during the Engine Room Arrangement Model (ERAM) project is available [DeVries, 1997].

#### Team Building



**Figure 2**  
**Box Representation of CAL/NCC**

Assemble a cross-functional process improvement team. In U. S. shipyard tradition, production and design functions are often barely on speaking terms. However, since participation, cooperation and commitment are needed from design and loft functions and the ship fitting shops, a cross-functional team that includes players from each of these areas must be established. Emphasis must be on team building with an investment in team building training, such as concurrent engineering training.

Trust and healthy interpersonal dynamics were established on the YARD BUSL team using a method gleaned from the construction industry: mutual goals were agreed upon and basic rules of interpersonal conduct were established. Basic ground rules of behavior were established and enforced by the team, such as practicing the art of “good-mouthing” one another and other rules of interpersonal conduct. Most important, agreement was reached to handle problems that occurred within the team. These few simple ground rules had as much to do with the success this team experienced as any other single factor.

Of all the factors that lead to success in any re-engineering project, building a healthy team dynamic is probably the most neglected aspect. Key workers will be understandably concerned with job security, or jobs disappearing as a result of implementing a more efficient CAD/CAM process. A key to success is a commitment on the part of the process owner that no one would lose his or her job as a result of CAD/CAM. Traditional tradesmen should be given the assurance that they will be cross-trained to perform not only traditional job

functions, but engineering and design work as well.

Establishment of Objectives and Goals

Typical goals include:

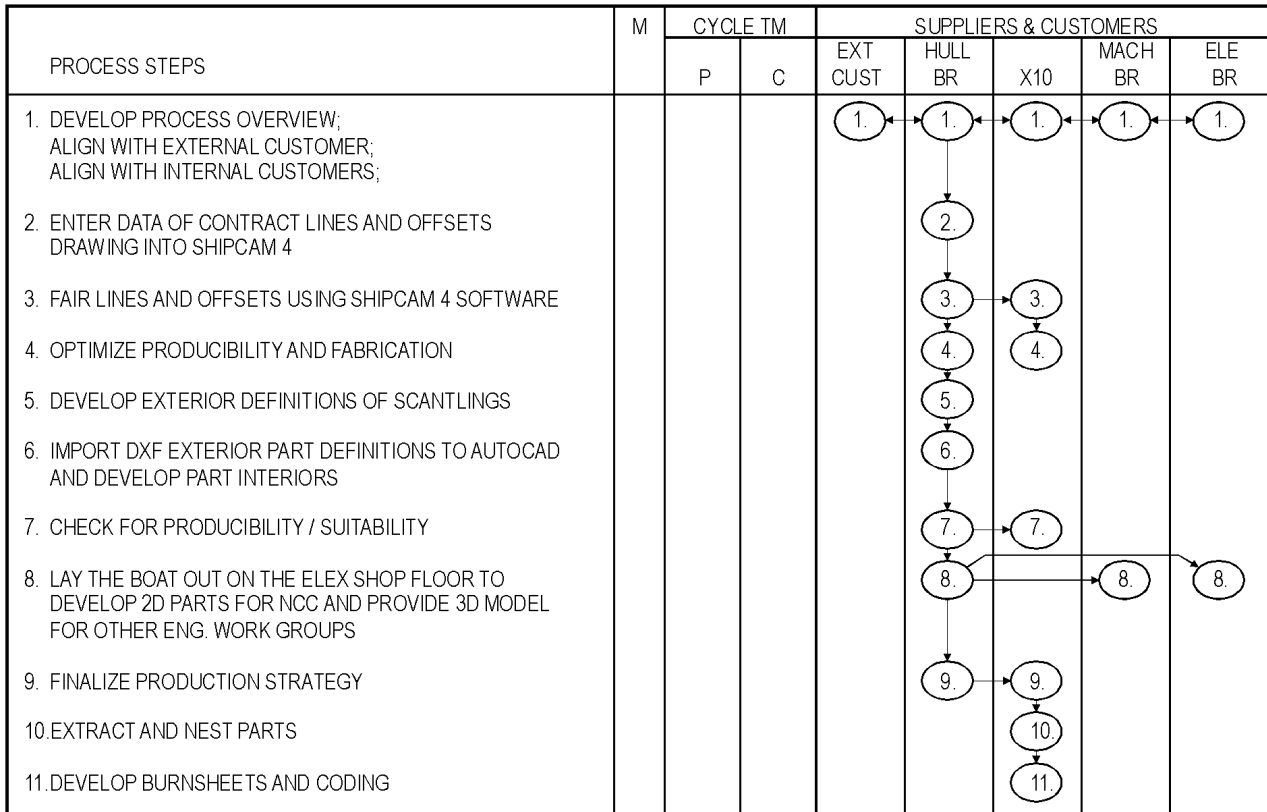
- Meet internal and external customer desires for ease of use, timeliness and certainty
- Minimize costs while improving product quality
- Provide a consistent, documented, repeatable level of quality, especially timeliness
- Accurately predict, monitor and compare (to industry leaders) key indicators of process success, such as cycle time, labor costs, product (including interim product) quality and schedule performance
- Provide a steady workload and reliable, secure employment for the workforce with opportunities

for team contributions

- Ensure that all interim products add an appropriate level of value; where interim products are contract requirements but fail to provide added value (frequently a result of obsolescence caused by the CAD/CAM technology) try to modify them by involving and educating the ship owner;

PROCESS: INTEGRATED DETAIL DESIGN AND LOFTING  
 OWNER: HULL BRANCH CHIEF

PURPOSE: TO DEVELOP DETAIL DESIGN DRAWINGS THAT AUTOMATICALLY GENERATE THE ELECTRONIC DATA FOR THE NCC'ING OF SCANTLING PARTS  
 INPUTS: CONTRACT HULL LINES, SCANTLING GUIDANCE AND REQUIREMENTS, GEOMETRIC CONSTRAINTS, CUSTOMER'S SPEC, STRUCTURAL CALCULATIONS  
 OUTPUTS: "BURN DISKS" (NESTED PARTS IN ELECTRONIC FORMAT) READY FOR NCC



**Figure 3 Swimlane Representation of CAL/NCC**

- Automate processes where appropriate, including production processes, CAD, purchasing, and logistics support.

**External Customer Alignment**

The form of information available from CAD/CAM adds new options to satisfying the final owner/operator of the boat, so aligning the process with customer expectations is a necessary step. Modern shipbuilding methods often require data in non-traditional formats. For example, data for plate cutting is expressed exactly in the electronic files of the drawings themselves, which show the exact shape and dimensions of all the parts. Additional dimensioning adds no value to the construction process, but drawing standards often require such dimensioning. Another example: end users usually need drawing data organized by system oriented classifications whereas the builder may need geographic (Zone) or process (Process Work Breakdown) orientation of data. Therefore, this dynamic between the external requirements of the boat operator and the internal needs of the production shops must be addressed up front in the

technical planning stage of the project. Development of the process overview, together with a Quality Function Deployment (QFD) approach allows all of these needs to be systematically addressed.

This process of alignment with external customers was not fully implemented for the 49 BUSL project because the data needs of the boat owner, who was also a Coast Guard entity, were already well known and well defined. In retrospect, a formal alignment process would probably have benefited the process by giving the owner a better understanding of YARD processes. In turn, this would have allowed modification of the drawing and other data requirements to streamline design and retain the value needed for the operators. As a result, the YARD produced drawings in conventional 2D format, organized by a Ship Work Breakdown Structure. This requirement had negative impact in that unnecessary drawings and drawing features were developed.

**Systematic Development of New Processes**

Develop a strawman process flowchart as a starting point. This allows those assigned to the task of

implementing CAD/CAM to focus on the important implementation issues resulting in reduced initial “storming,” and confusion. Identify and prioritize opportunities for improvement by establishing a detailed plan for implementing changes. This requires a formal approach to eliminate overlaps, oversights and non-value added products. A method for accomplishing this is “Boxing the Process”, in short, it consists of assigning responsibility to specific individuals for fleshing out the details of each step in the new process. Figure 2 is a boxing diagram for the NCC process.

Figure 3 shows the same workflow in a “swimlane” format that emphasizes the relationships between internal suppliers and customers within the process. Depicting the workflow in this manner helps emphasize those areas of the process where cooperation and alignment are particularly important. These boundaries, “the white spaces on the organization chart,” are where the greatest potential for inefficiency and problems occur and are the areas of greatest interest.

#### Internal Customers Alignment

Alignment between internal functions has such a dramatic impact on productivity and efficiency and is so easy to miss that a formal alignment process should be used to determine internal customer needs and interim product features and functions. Alignment here means establishing specific requirements for interim product format, features, and functions and resolving and balancing competing needs and desires.

One example was specific requirements for responsiveness to design changes after the drawing release for production. The YARD Engineering department had a standard of verbal response to a proposed design change within two hours with documentation to follow within two working days. This resulted in virtual elimination of unauthorized shop floor changes and hence very little cost in updating drawings to “as-built”, not to mention reduced rework.

The important interim products that design provides to production must be identified. For the NCC process the products include:

- Fiduciary Marks or “nick ons”: These are marks on the steel plate made with a zinc jet, pneumatic punch or low voltage plasma torch head when the plate was cut. They show where to attach a stiffener or other part, dimensions, location markings, accuracy control markings, reference lines, and are exactly placed by automatic machinery.
- Coding: These are part names, numbers and locations and can be added by either automatic machinery or by hand since they do not have to be exactly located.
- CAD files of the nested plate;
- CNC torch control code;

- CAD files of three dimensional parts;
- CAD files in DXF format and
- Text files of offsets.

The desired functions for these products is obtained and prioritized through the “Voice of the Customer” (VOTC).

At the YARD, the production shops were asked to complete statements in the format: “a quality (interim product) is one that is \_\_\_\_\_.” Typical responses were phrases like “easy to use”, “timely”, “defect free” and “A quality (interim product) is one which has \_\_\_\_\_.” These VOTC attributes were then organized and sorted into three categories: Timeliness, Ease of Use and Certainty. Examples of VOTC attributes for fiduciary marks and coding are shown in Figure 4.

The VOTC attributes must then be translated into precise, measurable Substitute Quality Characteristics (SQC), product characteristics that are designed into the products and then managed. SQCs have a clear relationship to the VOTCs and can be measured against an objective performance attribute. SQCs are developed by asking “How long...?” How many...?” How Often...?” How Much...?” The example SQCs for fiduciary marks are on the top row of Figure 4.

The relationships between VOTCs and SQCs are then determined. In Figure 4, minus signs depict an inverse relationship (as the value of the SQC goes down the satisfaction of the customer goes down;) plus signs (+) indicate a direct relationship (as the SQC goes up satisfaction goes up). Zero (0) indicates no apparent relationship. These are specific hard measures relating the satisfaction of internal production workers of the CAD/CAM process.

The SQCs are then prioritized by adding the number of relationships, both plus and minus, for each SQC. This identifies and prioritizes product attributes. A target value for the SQCs is selected as the basis for communication between the internal customers and suppliers in the CAD/CAM process. This process quantifies and prioritizes the desires of the production shop internal to the CAD/CAM process.

The VOTC table provides valuable input to the first QFD matrix, which is used to further refine the needs and priorities of the internal customers. The QFD allows zeroing in on what is truly important and should be addressed first. This is the first of the four stages of Quality Function Deployment. The same process is used to relate Product/Service Characteristics to Interim Product Characteristics, thence Process Characteristics and finally necessary Process Control Characteristics. This stage by stage relationship is the four Quality Function Deployment Matrices shown in Figure 5.

At the YARD, the result of this alignment process for fiduciaries was improved accuracy, reduced error,

PRODUCT: FIDUCIARY MARKS		SUBSTITUTE QUALITY CHARACTERISTICS							
		HOW MANY MANHOURS ARE SAVED SORTING THE PIECE PARTS?	HOW MANY TIMES DO SORTERS AND ASSEMBLERS HAVE TO STOP TO ASK WHAT MARKS MEAN?	HOW MUCH TIME IS SAVED DURING ASSEMBLY?	HOW OFTEN DO ERRORS OCCUR DURING ASSEMBLY?	HOW MANY MISTAKES (INCORRECT MARKINGS) ARE THERE?	HOW MANY MANHOURS DOES IT COST TO MANUFACTURE MARKS?	HOW LONG DOES IT TAKE TO READ THE MARKS?	
PRODUCT ATTRIBUTE GROUPS	VOICE OF THE CUSTOMER								
	TIMELINESS	SPEEDS UP SORTING, PALLETIZING OF PARTS WITH SIMILAR MANUFACTURING REQUIREMENT	+	-	0	0	-	0	-
		DOESN'T TAKE LONG TO MAKE FIDUCIARY MARKS	0	0	0	0	-	-	0
EASE OF USE		EASY TO READ (READABLE, LEGIBLE)	+	-	+	-	-	0	-
		EASY TO UNDERSTAND	+	-	+	-	-	0	-
		MAKES ASSEMBLY EASIER	0	-	+	-	-	-	-
CERTAINTY		MAKES ASSEMBLY MORE ACCURATE	0	-	+	-	-	-	-
		DOESN'T COST MUCH TO MAKE & USE	0	0	0	0	0	-	-
		DOESN'T HAVE ERRORS	0	0	-	-	-	0	0
		CONSISTENT SYSTEM FOR READING MARKS	+	0	+	0	0	0	0
	PRIORITY	4	5	6	5	7	3	5	
	TARGET VALUE								

Figure 4 VOTC Table For Fiduciary Marks

elimination of non-value-added drafting labor, and considerable time saved on the shop floor. It is worth noting that the few assembly problems encountered were all related to those markings that were not initially included in the formal alignment process.

#### Get Expert Help, Train, and Document

Expert guidance specific to the shipyard's equipment, physical plant, proposed processes and in-house expertise should be obtained for documenting processes (which may include software customization) and training. At the YARD, two full days were spent with a subject matter expert mapping out the CAD/CAM process in exacting detail. The expert also developed several key pieces of software. At Munson, one of the authors was hired specifically to fill this role, but nonetheless, other subject matter experts (two of the other authors) were also brought in. During this phase, detailed work instructions are developed which document the critical steps of the CAD/CAM process right down to the keystroke.

Integrated, internal, focused CAD training is critical to obtaining improved productivity with the new processes. CAD training from general sources such as community colleges has value in initial implementation, but success results from providing very specific, targeted, training just as it is ready to be used. Each designer and lofters must receive one-on-one training to ensure there are no misunderstandings regarding what was required and to become qualified in their role in the new processes. As little as possible should be left to chance. If you think of

it, discuss it, document it, and train in it. This approach enhances understanding, provokes communication, and provides the baseline upon which to make very specific improvements.

All quality desktop based CAD software packages have a programming language. This provides a tool for automating processes, but even more important, it provides a tool for standardizing and essentially documenting, via software, the processes. These customized routines standardize processes by ensuring that the correct layer is used for critical steps; that the unit system is correct and so forth. The routine initially developed for the YARD's weight extraction process neglected to set standardized units and the resulting data files required downstream rework to be useful. From this point of view, the value of task specific routines is much higher than would be suggested by pure labor savings. This again emphasizes the value of carefully identifying the form of an interim product by a formal process.

#### Develop the Schedule Strategy

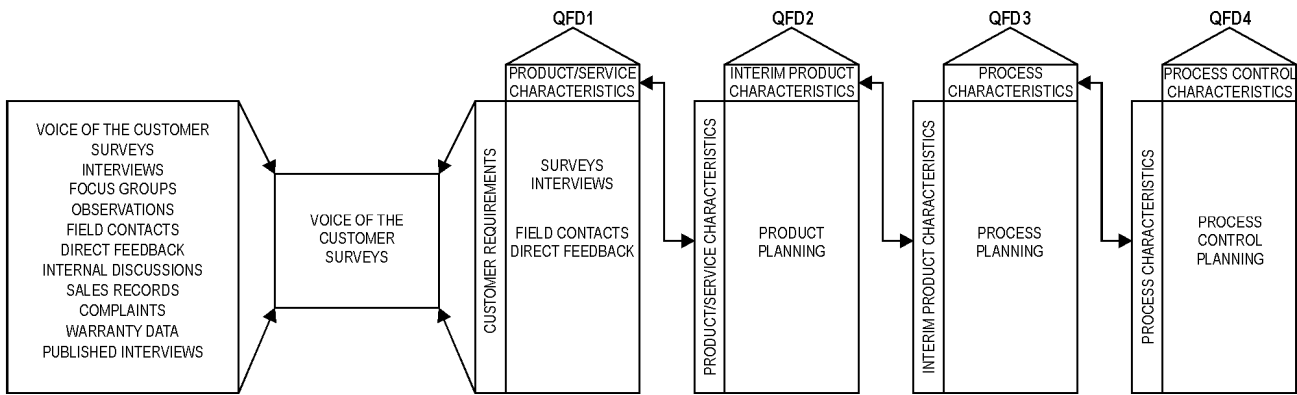
*"Never rush steel"*

**Richard L. Storch, IBEX West 95**

One of the biggest opportunities for inefficiency in the CAD/CAM process is differing expectations for schedule and sequence between the external customers, (and often senior management) and production. The sequence and rate of construction will determine the order and schedule of part cutting and hence the requirements for the design and lofting schedule and for manpower. More important, it will have considerable affect on the coordination of all aspects of production and even basic production strategy. Customers often tie payments to specific events, despite the fact that the only truly meaningful event to the customer is delivery. Likewise management often sets up schedules based on manloadings or other needs without fully understanding the effect on production. During the BUSL project, such schedule requirements resulted in cutting steel for several boats before penetrations were fully located, thus causing rework and lost productivity. Obviously, these other schedule needs are real, but it is important to use the same alignment process to balance these competing pressures.

#### Develop Construction Strategy Based on New Processes

CAD/CAM produces extremely accurate parts, eliminates floor fitting and facilitates elaborate, inexpensive cutting details. This provides for radical changes in construction processes and strategy as discussed below. Again, this requires specific, technical alignment. Both production and design functions must



**Figure 5**  
**Quality Function Deployment Matrices**

have “profound knowledge” of each other’s processes, needs and capabilities to find opportunities for productivity improvements with CAD/CAM.

#### Measure Results and Repeat

The last step of the formal process is to systematically measure the results, return to step one, and improve again, based on the greater “profound knowledge”.

#### Outside Design Agents

*“Being careful isn’t nice – being friends is better”*  
*“A Bargain For Frances”, Hoban & Hoban*

Many small shipyards do not have the resources to maintain internal design or lofting functions, requiring the use of subcontractors. The industry as a whole can develop generalized standards, but shipyards will always vary in their needs due to differences in equipment, skill of labor pool, product line, etc. Design agents will bear the main responsibility of alignment because they are the top level suppliers.

The effort of alignment, and the fact that each side will generally have to give something to achieve the best possible overall outcome means that design agents and shipyards should plan on entering long term arrangements to bid and accomplish projects over a span of some years. In order to make this successful, some form of partnering and risk sharing must be established, linking the design agents profits with the gains of the shipyard.

Another important aspect is that the need for incorporating shipyard specific production features in even the most basic design elements will further accelerate changes in the basic process of ship acquisition: Traditionally, a ship owner goes to a design agent and gets a contract design. This is then bid out and awarded. The contract design agent cannot do the detailed design, or the lofting, due to conflict of interest.

This inevitably results in the loss of valuable data between the contract designer and the detail designer. Design agents need to address this problem through industry wide cooperation.

A final important aspect of CAD/CAM for designers is the owner/builder concept. In some cases, CAD/CAM allows an owner to obtain what is basically a complete kit for building a small ship. As a result they can dispense completely with normal shipyards and build a ship just as they would a custom home, through a series of specialist subcontractors. Some Pacific Northwest fishermen and tug companies have built vessel as large as 100+ foot tugs and fishing vessels, completely outside of any shipyard. This represents a new type of customer for the design agent and greatly increases their responsibilities and the required scope of their expertise.

#### THE PRODUCT MODEL

Improvements in software design such as “object oriented” technologies are enabling an evolution from drawings to models in design projects. The difference being that a drawing of a part or assembly is composed of largely independent lines, arcs, and circles, while a model of the same part might be a collection of interrelated subparts or objects, presented in terms familiar to the designer [AutoDesk, 1998]. Objects have geometric aspects, data aspects, and “behaviors” [Gribskov, 1998], which allow input for rule based design.

A model inherently has more intelligence than a drawing and usually is a more effective way in which to develop and communicate a design. A model captures and stores design “intent”, as well as important information useable in other areas of the design and life cycle maintenance of a product. The product model of an entire ship is an integrated database that supports the informational needs of engineering, design, and production. [Ross, 1995] Ship product models have been developed using mainframe applications, but small

shipbuilders can use linked databases and simpler models to provide similar functionality through symbology, non-graphic data and by determining exactly what aspects of such a model add value.

The notion of a product model is certainly not new. Electronic product models are now used for aircraft, automobiles and in the process and power industry, and of course, we are seeing product models being developed for major warships and other large ships. The familiar set of drawings, specifications and parts lists can be considered a product model in that it is as complete a description of the final vessel as is required to construct it and maintain it through its life cycle. However, the concept of a product model implies a three-dimensional aspect. Mercier coined the phrase “electronic Admiralty model” as a synonym for “product model” to emphasize this. In the days when ships were wood and men were iron, designers used a scale model depicting hull shape, rig and structure to specify a warship for the lords of the Admiralty. Likewise, the electronic Admiralty product model gets much of its value by retaining the true three-dimensional aspects and the true dimensions of the ship geometry in a single database. Two dimensional drawings do not have this important data and require extensive interpretation and interpolation between various drawings to derive even the simplest geometry.

A product model is more than just a virtual ship that looks like the real thing. A product model contains non-graphic information, encoded as attributes into the entities, which are accurately located in a 3 space coordinate system. This additional information affords significant opportunities for process improvement, because virtually any information can be encoded in the product model. Use of encoded data and other techniques also affords an opportunity to reduce the cost of producing a product model.

#### **Use of mainframe vs. desktop systems**

One strong philosophy for CAD/CAM implementation hinges on the idea that it is more cost effective for a small yard to grow a shipyard construction and information management system using desktop computers. A small shipyard can combine desktop computers, PC based software tools, and some extensive, focused programming to create a tailor made construction management system. This is in contrast to the use of high end, workstation based systems that are purpose built for large shipyard construction, cost upwards of \$60,000 per seat, have correspondingly high maintenance fees, and still require customization through additional programming. This argument gets stronger as the PC tools become more powerful.

The majority of work on ship product models has historically been produced by mainframe/workstation based software specialized for ship design, such as

TRIBON, FORAN or Intergraph. Most of these systems use true solid entities and objects extensively. Solids are the most sophisticated and richest depiction of an object and are demanding in terms of file size and modeling techniques. These specialized software systems not only must handle large files, but must also provide aids to help make these complex entities semi-automatically. Even though most PC based software systems can deal with solids, the file handling requirements are such that desktop general purpose CAD/CAM systems are only now becoming powerful enough to build a full-generalized solid model of even a small, complete ship.

General purpose CAD programs have a number of practical advantages, however. In general, a ship production “suite” of programs such as AutoCAD combined with additional third party ship design software, is less expensive and runs on less expensive hardware. Programs such as CAD-Link, and Microsoft Access can be combined with a PC based CAD program to create a powerful ship product modeling tool. Although one or more specialized third party applications are required at a shipyard to handle specialized tasks such as hull fairing or piping design, these are only needed for a few specialized workstations, which reduces the average workstation cost still further.

The sheer size of the major general purpose CAD vendors also provides advantages. For example, there are some 1,800,000 AutoCAD licenses held worldwide. There are numerous US periodicals exclusively devoted to specialized, PC based drafting products and techniques, and thousands of active users and third party vendors developing software and techniques, often for very low costs. Vendor drawings are frequently most accessible in PC CAD compatible formats. Training in AutoCAD and its competitors is readily available, often in community colleges or even high schools. Many shipbuilding problems are similar to those found in other, larger industries, so there are a range of readily available applications that can be adapted to shipbuilding. Finally and perhaps most important, there are literally millions of trained AutoCAD operators available. The problem is how to achieve the functionality of a product model within the limits of general-purpose software.

Surface and wireframe models are three-dimensional. The wireframe model only depicts edges or centerlines of parts and is significantly less costly than a solids model. However, a wireframe model, especially in combination with attributes, can encode all of the data to actually build and maintain a ship. Only the path of the numerically controlled torch that burns out a part is required to fabricate it. Likewise, the only data needed to cut and install a stiffener is its length, end treatments and location. Information can even be in a separate database, provided the product model can automatically link to such a database. The fact that the product model consists

of multiple files is completely transparent to the user. Jolley [Jolley, 1992] used such a scheme to dynamically generate stiffener details. This system not only allowed the drawing to drive the database, it also allowed the database to drive the drawing, so that stiffener detail drawings could be automatically generated from the database.

Though it is possible to make a solid model of a valve, pipe, or fitting, such a model is not necessarily required, because the shipbuilder is not making the component, only placing it in a given point in space. It is only necessary to encode a part number and the location and orientation of the part. The part numbers then can be automatically extracted and cross referenced to a catalog of parts to produce a bill of materials. This approach loses some advantages of interference control, because the entities designating parts do not necessarily have the correct shape or volume. Nevertheless, small ships are generally simple enough to make manual interference checking possible.

A solid entity “knows” its own volume and material properties, such as density, intrinsically, so that weight can be readily extracted. While depicting steel as a wireframe model consisting of torch paths loses this explicit weight data, there are other methods that weight can be encoded: In the BUSL project the steel was shown as wireframes. To get weight data, each steel part was attributed with a “partinfo” block automatically through custom routines that calculated the area properties and center of gravity of the part based on the torch path and coded thickness and material. The designer input the type and thickness of the material, selected the burn path and ran the routine. The routine automatically calculated weight and center data and inserted a partinfo block with this data as attributes, along with part number and other data. The weight manager extracted the data from each drawing’s file to a database management program.

Although at first glance, this was not as simple nor as “clean” as interrogating a solid model, it had an important benefit: other parts that were ordered rather than fabricated had similar partinfo blocks, also with weight data obtained from a catalog or scale weighing. This meant all weight data was consistent in format, and when estimated weight data for a part was replaced by scale weighed data, the database remained consistent.

It is important to keep in mind that we only need to make a model that is good enough to satisfy our real needs in manufacturing, installation, or the owner’s requirements. After all, the current system of orthographic drawing is not photo realistic views or even artist’s conceptions. It is a system of conventions and symbology that economically depicts the data required to build a ship. This traditional system evolved over many years and is so familiar that it is virtually transparent, but

it is the result of a process of evolution relentlessly focused on value added. A similar process must be used to produce the least expensive, most effective electronic product model.

### **Tailoring the product model**

We have to use the tools of process engineering to determine the most useful form of data, and to encode that data in the model. This will greatly depend on the various downstream customers of the data, including the vessel owner as well as the production workforce.

Munson, because it built more or less standardized workboats, had highly evolved standards, with pre-designed work packages, for many systems. There was no need to even include data on most systems in the vessel design. Only structure and joinerwork needed to be depicted, so only simple data was required.

A builder serving a more sophisticated market may have to produce extensive conventional drawings for use in either construction or for the owner. He will have to develop modeling conventions that make production of such drawings easy.

A yacht builder will probably use the product model for marketing, so photo-realistic appearance may be required for many spaces, despite the fact that it does not add value to production. (This might seem to require very expensive models, but there are many software tools from the computer gaming industry that achieve an acceptable appearance at reduced cost. For example, you can “wrap” scanned photographs on elementary shapes to give the appearance of a complex object without actually modeling it.)

The speed at which computers and software evolve also requires continuously modifying modeling conventions. Tailoring the product model to new needs will continue forever, just based on this alone. However, this requirement for continuous improvement based on software change is an opportunity for continuous process improvement as well.

Fiduciary marking is an example of use of symbology and coding to reduce modeling costs as well as an example of the alignment process as discussed above. Fiduciaries reduce modeling effort for stiffeners because the designer only marks a line where the stiffener touches the plate, generally with a “toenail” or mark to indicate the flange direction and a “meat mark” to show which side the thickness of the stiffener lies on.

Fiduciaries are generally placed with a custom routine as well, so that they are on the correct layer and contain the correct attribute data, as well as to reduce labor. The part number associated with the fiduciary encodes the weight in its proper center of gravity, and since the fiduciary will actually appear on the plate, the drawings need not be dimensioned, and workers won’t even need a drawing.

The use of fiduciary marking is as big a savings as

numerical cutting itself, provided that all customers' needs are met by the marking system. The alignment process at the YARD required balancing the complexity of the marks against the limits of the rather old pneumatic punch installed on the YARD's CNC torch and agreeing on symbology conventions and how data such as end cuts and stiffener length is to be transmitted. The formal process that resulted in fiduciary standards is documented above, and the key was to develop the most important features of the fiduciary mark product. As the construction processes evolved, the product features also evolved, but the process was in place to allow continuous improvement. At the YARD, end cuts were initially depicted by symbology on the fiduciaries and length in the bill of materials (extracted from attributes in the database), but later both length and end cut data was transmitted in a separate database referenced by part number. This choice was driven by the organization of stiffener production in a shop, and as the shop became more confident about the data in the product model, their processes and hence the form of the data they requested, changed. Finally, the YARD had to align with the external customer as well; the operator of the ship to agree that they didn't need dimensions on the as-built drawings and could accept the shop symbology.

#### **Life cycle use of the product model**

The product model also represents an opportunity for the ship owner and operator. Some analysts claim that AutoCAD is being used to redraw more existing facilities than new ones, because many such plants are being managed by use of a combination of AutoCAD and linked databases. Petrochemical plants are linking maintenance information to drawing files and shopping centers are linking tenant financial data to drawings. The idea is to use the drawing as the fundamental tool to navigate through the entire database of a facility. Especially on shipboard, this is a powerful tool because so much data has important three-dimensional aspects, from compartment and access data to ship alteration weight management. Any type of data can be linked to the product model, even real time instrumentation data. Since these links can even extend outside of the product model itself, the possibilities are almost limitless. A trite notion, but one that could radically reduce costs, is the possibility of linking the product model to the Internet, so that an engineer on shipboard can order a spare by clicking on it on the drawing.

### **BUILDING A PRODUCT MODEL WITH DESKTOP SYSTEMS**

#### **Fairing systems**

General purpose, PC based CAD programs do not provide good tools for fairing a hull surface or generating

the other parts of the ship geometry. Expanding plate or generating surface to surface intersections such as traces of longitudinals, and planar cuts like frames, sections, waterlines and buttocks require dedicated software. Third party software (ShipCAM at the YARD) must be used to fair the hull and accomplish these tasks. The key to efficiency here is simple; generate the hull shape in detail as a very first step, only generate the hull shape once, and ensure that all functions having interest in hull fairing buy into the final hull shape. Most lofting software links to hydrostatics software and so an immediate step is to perform stability analyses to determine weight and centroid limits for all contractual stability criteria.

#### **2D - 3D**

Drafting in 3D, particularly in desktop systems without specialized add-ons, is justifiably viewed with concern. 3D drawing is somewhat unnatural and requires experienced operators. In addition, owners feel that it will not give them the documentation they need to maintain the boat. However, the value of a 3D structural model for visualization, accurate geometry generation, interference checking, and weight management is so significant that such a model is very valuable. This problem can also be resolved in a variety of ways:

A combination of 2D and 3D processes were used at the YARD as an expedient for the BUSL project. This approach used a combination of standardization and some specialized software. This approach also controlled the configuration as required by ISO and ensured that all designers were using the correct data.

In the YARD, the designer with the most 3D experience was ordained the "Geometry King." He maintained the ShipCAM database and did all lofting functions required after the loft, the owner and design functions agreed on a faired surface. ShipCAM provides capability for extracting both 2D and flat 3D geometry. Both types of data are "polylines" or collections of linked line and arc segments forming curves. In AutoCAD 2D polylines have a consistent "extrusion" direction, or Z-axis, throughout their length, whereas 3-D polylines do not. Each segment of a 3-D polyline has a different Z-axis so 3D polylines are very difficult to modify and edit. To eliminate this problem the Geometry King gave other designers correctly oriented 2D polyline geometry of the molded surfaces derived from the ShipCAM model. Each designer developed the piece parts flat in 2D and made conventional structural drawings. The designers then passed the flat parts back to the Geometry King who placed them in the 3D model in their proper orientation for interference checking and configuration control. This process was actually very simple and effective.

The key to easy reinsertion of the parts and control of designed geometry was a procedure for preservation of the point of origin and axes throughout the design. When

the Geometry King extracted the molded surfaces, he also extracted the current location of the boat origin in the 2D plane of the parts and the Z (out of plane) distance to the origin. He preserved this point on a dedicated layer and attributed it with the Z dimension plane, and the piece part or view applicability. The designers preserved this point and its location relative to the piece parts throughout the design process. Later, the Geometry King reinserted the finished part with the preserved origin at the model origin, rotated and elevated as required. This was a key procedure and was supported by specialized Lisp routines and origin blocks to eliminate errors.

Another interesting technique used late in the project (as designers became bolder and more CAD files were available from vendors) was modeling purchased components as “crossed paper dolls”. The three views of a part were each oriented in its correct plane. Then the views were placed so the nominal origin point (the shaft center and block face of an engine, for example) of each view coincided. Blocks were added at the correct location of all interfaces and attributed with whatever information was desired (weight, fastener, pipe size, flow, temperature, voltage, price). If necessary, the part was surrounded with a simple shape to indicate clearance for the actual part and for maintenance (which was on a separate layer.) Then the part was connected to the rest of the ship. All of the necessary information was right at hand, and when the model was viewed from the standard orthographic points, it automatically generated acceptable conventional drawings.

All in all, the use of this hybrid, interim, “2 ½ D” procedure worked out very well. There were no bad parts and the design of the structure proceeded very smoothly. The time lost in the redrawing required by orthographic representation and part reinsertion was small compared to the loss of productivity from designers uncomfortable with 3D. Most important, this process has provided a smooth bridge to more elaborate use of 3D, and such features as Paper Space, XREFs and CAD/Database interaction. Many designers had experimented with these features in some of the drawings by the time the structural design was complete. The deckhouse was designed and detailed in full 3D and presented partially in Paper Space. A piping system and a partial piping composite were built using Paper Space, simple database interaction, and XREFs, and hence constituted the first steps to a full product model.

### **AutoCAD Features**

We again mention that the author’s primary experience is with AutoCAD. It is worth a detailed discussion of some specific features of AutoCAD that help in the product modeling process for those that are not familiar with the program. (Most CAD software has analogous features):

A User Coordinate System (*UCS*) is a local set of named coordinate axes that may be used to create entities or derive information from them. The UCS is a key to using 2D techniques to build a 3D model. The designer just works in a plane defined by a particular UCS and need not be concerned that the “real” origin of the part he is developing is located somewhere else and may be rotated in all three axes relative to his work.

AutoCAD provides “*blocks*”. These are combinations of other basic entities in a drawing. A block is usually a small drawing such as a symbol, that is a part of another drawing. The block exists only once in the drawing database and is inserted into various locations in the drawing by reference (which means it reduces the drawing file size as well). A block may consist of entities on various layers, and exists (is “inserted”) on a specific layer. A very important feature of blocks is that they can contain “*attributes*” or non-graphic entities that can link to other databases. One key to the product model is to make blocks of purchased components with appropriate attributes and insert them essentially as components. One small warning however; do not insert part information in a special part information block with the desired attribute templates and then, subsequently insert that into the component block. It will be very difficult to access the part information block due to the depth of its nesting once it is inserted into the product model. Instead use a standard component template and build the component block on it.

AutoCAD provides named “*layers*”. Entities exist on layers and a layer may be current, on, locked, off, or frozen. The current layer is the one that entities are in as they are being created. A layer is on if the entities in it are visible, plot and can be modified and “snapped to” (specific features such as endpoints of lines can be used to exactly place new entities). A locked layer is visible, plots, can be snapped to, but cannot be changed or erased. A layer is off if its entities are not visible or do not plot. Entities on layers that are turned on and contained in a block, are visible even if the layer the block is inserted on is off. A frozen layer is not visible, and any entity in a block inserted on that layer is also not visible, even if they are on another layer. Layer naming and standardization is very important in producing a useful product model, as layer names are a key property for sorting entities.

*Paper space* is a powerful but often confusing tool that is frequently underused even by experienced CAD operators. But once understood, it is actually very easy. An AutoCAD drawing (after R11) has two modes, *Model Space*, which is three dimensional, and *Paper space*, which is two-dimensional. Paper space allows the designer to set up a “virtual sheet of paper” that consists of “*viewports*” looking onto the three dimensional model. The viewports on the three dimensional model can be

looking in any direction on the model, at any scale. The viewport may have clipping planes (set up by the “*DVIEW*” command) such that it only sees a certain depth of the model: any portion of the model not between the front and back clipping plane of a viewport will not be visible in it. Each viewport may have a different set of layers frozen. Frozen layers will not be visible in that viewport, but may be thawed and visible in other viewports. Thus, one viewport could show one type of piping in the product model, and another viewport a different type. Paper space is the tool to make conventional two-dimensional drawings out of the 3D product model.

*ASE* is AutoCAD Structured Query Language (*SQL*) Environment. This is a two-way interface between the AutoCAD file and *SQL*, which is a standard interface for most database managers. This reduces the amount of data required to be loaded in an AutoCAD file and allows a drawing to access data not in the file. It also allows other databases to modify the AutoCAD file.

*XREFs* are the essential tool for compiling an accurate and manageable product model in AutoCAD. An *XREF* is an “external reference” within an AutoCAD drawing, which calls another independent AutoCAD drawing. By using *XREFs* and a series of individual part drawings, an accurate three-dimensional product model can be compiled.

Although the physical characteristics of *XREFs* are similar to *BLOCKS* within the active drawing, *XREFs* differ from *BLOCKS* in that they are not part of the active drawing file itself, but rather are “called” each time the active drawing is opened. Therefore, if one or more *XREFed* drawings are modified, the active drawing is automatically updated without any required input or tracking by the operator each time it is opened.

A major benefit of this tool is that it allows any number of designers to work on all aspects of the vessel concurrently. Normally only one draftsman could work on a single drawing concurrently. Through the use of *XREFs*, it is now possible to have many designers working on a specific system or part of the vessel in individual part files. These files can then be *XREFed* into a composite drawing and a series of sub-assembly drawings. If a revision is made to one or more of the individual part files, updating any drawings affected by the revision is simply a matter of opening the affected drawing.

Another important aspect is that in most cases, each piece of geometry need only be created one time. Using *XREFs*, individual parts can be attached to any number of other drawings to compile sub-assemblies, assembly drawings and composite models. Because each piece of geometry is properly oriented in three-dimensional space with respect to the origin of the vessel model, it is possible to generate a series of views of an assembly or

composite model from different vantage points. This can be of particular value to workers on the shop floor, especially for complex assemblies. This also allows for interference and tolerance checking.

Individual part files contain only the basic geometry of the part. Borders, backgrounds, dimensioning, callouts and other standard drafting elements are added in the assembly or composite drawing.

An essential key to efficiently integrating these tools while maintaining accuracy and efficiency is to maintain an organized directory structure in which all parts and assembly drawings are stored. It is not uncommon to have hundreds or even thousands of individual part files even on smaller vessels. These files can become a digital rat’s nest of information if not properly managed.

*XREFing* in its current form does have its limitations. Along with careful management of the directory structure is the necessity for strict standardization of layering, blocking and line type conventions. Moreover, some components must be managed in two forms, the first being the form in which they exist in the vessel, and the second being the form in which they are fabricated. An example of this is shell plate. A file representing the three dimensional form of the part is required for a sub-assembly or composite model. An expanded plate format must also be developed representing the plate as it is CNC cut and delivered to the shop.

AutoCAD addresses some of these problems with the *ADE* (AutoCAD Data Exchange). This facility allows building drawings up by a process similar to *XREFs*, but with substantial automatic aids. A designer building a given drawing can reach out to other files and bring into his file data sorted by layer or other properties, including attributed data, and clipped by location. A program such as *CAD-Link* also facilitates this approach by tying the CAD geometry of each part or component to a ship report database. The program also allows for convenient management and use of yard standard components and materials in the building of the vessel product model. New software is constantly being developed to further streamline this process.

These basic features suggest a concept of how we can build a product model with a PC based system. Each system is developed comprising of only the components in it, with no background, dimensions, or other conventional drafting elements. A system may also be divided into a series of subdrawings that are separated into regions of the ship, thus providing zones of structure or outfit. The system can be designed with *XREFs* of backgrounds of other systems, and when it is complete can be stripped of everything not ordered with that system. Conventional composite system drawings can then be made with *XREFs* of sub-systems, adding *XREF* backgrounds as required, developing Paper Space views

of the system and adding dimensions, notes and other drafting elements in Paper Space. A three dimensional view can be assembled with XREFs of all of the desired ship systems and structure into a single drawing, again with no drafting elements. Zone assembly drawings can be made with XREFs of all components in a space. Pipe spooling data or similar piece part fabrication data can be made with XREFs of just the system components, adding the fabrication data in Paper Space. The product model thus consists of all of the individual system models plus their linked databases, and we can access any and all data associated with the model through any of the drawings generated by this process.

### **Software for structural design**

There are four main problems for practical structural design in CAD:

- The basic geometry of the ship cannot be conveniently dealt with purely within the CAD tool, and an external fairing program is generally required to develop ship geometry
- Solid modeling is cumbersome in a bare CAD system
- Some parts must be expanded or have other fabrication steps and thus must be represented in two or more forms in the model
- All steel must ultimately be nested on plate and cut

Each of these issues can be dealt with by free standing software, but if any aspect of the structure is changed during construction, the changes should be automatically reflected into the CAD database modified throughout, all the way to plate nests. It would also be nice to have tools that provided easy ways to add the myriad of standard steel details. These are basically technical problems, and as noted above, any purely technical problem probably is addressed. The use of Windows 95 or NT allows much tighter linkage between software than previously and applications have been developed to take advantage of this for structural design and detailing.

CAD-Link is software that works within AutoCAD, using these sophisticated features of AutoCAD ADE and Windows to achieve exactly this. Several similar programs for marine structural design have been developed recently for these advanced PC environments. CAD-Link provides a library of shapes and tools for direct solid modeling of structural components with input in either 2D or 3D and numerous file management tools for generating databases of structure and plate nests of parts. It is also tightly linked to fairing software and piping software. It is currently in use at several shipyards producing effective product models.

### **Piping Design Software**

Desktop system software for piping design is also available, and it is interesting to explore how such

software works. A piping system can be completely described in a basically numeric and text database. For example, a given system could be described as "beginning at x,y,z, place a fitting, then six feet of {type} pipe to x,y,z location" and so forth. A number of piping programs use exactly this kind of data, and automatically generate an isometric drawing, orthographic drawings, schematics, or a 3D model, as requested out of the database. In turn, they provide tools for generating each different type of drawing so that the fundamental database can be derived from them, also automatically. Although it is possible to produce full three-dimensional piping product models without extensive third party piping programs, the programs provide greatly improved functionality. This is mainly because they allow the designer to describe the system in terms of real world components (from the program's library) rather than geometric or drafting entities. In other words, a system designer doesn't draw arcs, lines and circles, he places pipe, valves and fittings, just as if he were really building the system, and the software takes care of the drafting automatically.

### **Standards**

Clearly, a key to the development of a product model is extensive standardization. Files, layers and layer names, attributes, coordinate systems, and components all must be organized and standardized. This standardization must be done using an alignment process that includes all users of the product model, especially purchasing and logistic functions, as well as production and design.

### **Training**

The need for training has been noted before, but it is worth repeating. A CAD operator, even if nominally trained in school, will require the better part of two years to be highly productive. Even after basic training, learning continues and should be supported. Continuing education in the form of less formal training is probably more valuable than formal training, and it is certainly cheaper. Every office should subscribe to all of the CAD magazines covering their software - one routine out of "Hot Tip Harry" [Liddle] will pay for the subscription to CADalyst many times over. Other training aids include books, videos, Internet sites like the AutoCAD Users Group International ([www.augi.com](http://www.augi.com)), and attendance at one of the many CAD industry conventions. It makes sense to designate a CAD librarian to collect and archive routines, blocks, and other data as well as training aids.

However, the most effective means is peer-to-peer training. Probably no CAD operator is fully capable in every aspect of the software, but some combination of operators will know most of what is required. Therefore, it makes sense to have the best teach the rest. The Coast Guard YARD has a monthly user's meeting over lunch.

One operator makes a presentation of some specific technique at each meeting. Time is set aside for each user to bring up problems and have them resolved by the group. This type of forum is also a valuable opportunity to further develop standards.

## DESIGN FOR NCC PRODUCTION

*“The second cut is free”*

*Anonymous steel service salesperson*

The elimination of cutting, measurement, and layout labor through the use of Computer Aided Lofting/Numerically Controlled Cutting changes the way ships are produced and thus the way they are designed. Accurate dimensional information can have an even more profound impact.

*Poke Yoka* (Japanese for “foolproof assembly”) are assembly aids numerically cut either in the part or in scrap areas of the plate. *Poke Yoka* includes shaped tabs cut on the edge of a joint to ensure it is mated to the correct part and aligned properly, slots or holes to hold parts prior to welding, clips to eliminate clamps or marks and other features to check accuracy. Either these features can be permanent, or more often are cut off after use. Besides facilitating assembly, *Poke Yoka* can be used to control accuracy between modules. A pair of identical dummy frames temporarily tacked to the joint where two modules will later be joined ensures that they will fit. A bar, cut to an exact length, fitting into pre-cut slots, maintains a critical dimension.

Roll sets are curved templates, numerically cut, and used as tools to guide bending operations. Roll sets are also *Poke Yoka*, especially if they are fit with tabs to ensure that they cannot be used except when placed and aligned properly. The BUSL had several plates that had to be pre-rolled, and though NCC cut roll sets were supplied, they proved to be difficult to properly locate and align, resulting in rework. In retrospect, the roll operator should have been consulted about his needs and *Poke Yoka* used to facilitate the operation.

Such details are feasible because elaborate cutting is very cheap with NCC. In fact, some steel service centers charge by the pound of raw plate placed on the burning table regardless of how much or how little actual cutting is done. (One of the authors thought to abuse this by copying several decade’s supply of standard pipe caps and hatch clips on a scrap area of plate. Several fifty-pound sacks of parts, none more than an ounce each, arrived the next day without any comment from the service. This incident again illustrated the need for alignment between functions - the parts department was most unhappy about being inundated in parts they neither needed in such quantities nor could store.)

Development of *Poke Yoka* definitely requires

careful alignment and teaming between designers and the production shop. One key is to ensure that the shop understands the capabilities of NCC and engineering, because they will almost certainly request aids for processes that engineering never even imagined existed once they know what they can get. This is a clear signal that you have succeeded in team building.

The capability to exactly define the shape of a hull and to cheaply cut parts that fit offers opportunities to change design, thereby reducing labor. Many Pacific Northwest shipyards now use flats instead of angles or tees as longitudinal stiffeners. They are numerically cut to the exact edgewise shape so no bending “the hard way” is required. This requires a change in the structural design of the ship - either the frame spacing must be reduced or the longs must be deeper or thicker. This also increases weight slightly, but reduces labor cost and, at least in aluminum, may reduce material cost as well, since scrap plate is cheaper than extrusions. Structure made this way is also easier to blast and paint.

Large shipyards use automated panel lines, semi-robotic conveyors with automatic equipment for seaming plates together and attaching stiffeners to them to make up large panels. There are relatively few large flat panels in most small ships, so panel lines aren’t very useful, but this concept can be modified to fit the needs of small ships.

Hull plates are usually developable. This means that they contain a series of rulings - straight lines - in the surface. By laying out rulings in their proper relative orientation so that a side or bottom plate is nearly flat, an adjustable jig can be set up. Since each ruling is straight, a collection of pipes with adjustable height stands at each end would suffice. A pre-cut plate is laid on this jig and the longitudinals, flat plate cut to the correct edgewise shape, are laid on the fiducials depicting the longs and tacked. If more section modulus is needed, especially for aluminum, a compact extrusion can be added, complete with weld prep, to make the flat plate into a bulbed shape. (Such an extrusion in aluminum would typically cost no more than \$600 for the die.) The compactness of the extrusion makes it easy to bend into the final shape. The production welding is done downhand with a weld pacer or “Bug-O” - basically a motorized clamp that carries a wire fed welder down the longitudinal member. For steel, gravity fed electrodes can be used instead. Sections of the transverse web frames can be placed over the longitudinals and welded down. Each plate can be pre-outfitted and pre-painted and the boat itself can be assembled by tipping up the sides just like the wall of a house.

This technique is a radically different way of building a small ship and design choices such as longitudinal and transverse frame depth and spacing will clearly be affected. Another very interesting point about

this technique is that it came out of a process focus meeting of shipfitters, not from management on high.

The product model potentially has other data available to use in CNC equipment. Two examples are worth noting: Weld paths can be developed automatically from the fiducials of the parts. These paths can be extracted for robotic welding applications. Weld path data can also be used to facilitate coating. It would be simple to add a CNC power brush or high pressure hydroblast head to the cutting system. This could be used to clean off primer in way of welds, so that non-weldable, more durable primers could be used.

### **Developable and Double Curved Surfaces**

A good understanding of developable surfaces is very important for small shipyards, because such surfaces play an important role in small ships and are critical to producibility. CAD/CAM allows much more control and understanding of design options with developable plate, but provides traps for the unwary as well.

A developable plate is a ruled surface everywhere, but having rulings is insufficient to ensure developability. Each adjacent pair of rulings in the surface must be coplanar within a small angle. Strictly speaking, the angle is zero, but in practice anywhere between three to six degrees of warp between rulings can be plated. However, any amount of warp other than zero means that there are an infinite number of possible developed surfaces between two chines, and many of these surfaces (usually those with the smallest warp angles) are not fair. Though most fairing programs can produce some form of developable surfaces, operator expertise is required to ensure fairness and producibility and preserve the designer's intent. Designers should also be aware that duplicating conventional waterlines, stations and butts with developable surfaces is very difficult. If you have a specific requirement for shape, preserve and tabulate rulings of the surface in a table of offsets.

Double curved plate requires additional downstream knowledge from the design functions and hence better alignment between processes. There is no unique expansion for a given double curved plate, hence CNC cutting such parts neat requires that the designer doing the part expansion understand the plate forming process in detail. A flat plate can be stretched or shrunk (or both) along any single or any combination of axes to produce the required curved part. As a rule, in small shipyards, steel is line heated to shrink it and aluminum is stretched, usually with an "English wheel", but the axes of the deformation must also be specified to ensure that a plate will expand properly. This suggests that the designer should mark line heat or wheel passes. This would improve worker productivity as well, but again requires alignment and team building, especially here - plate-forming operators are justifiably proud of their expertise.

### **ADVANCED OUTFITTING/GROUP TECHNOLOGY**

*"We always make money on aluminum, but outfit eats our lunch"*

**Bill Munson**

Advanced outfitting is the process of installing machinery, piping, wiring, joinery and all the other components that make a big weldment into a ship before the ship is structurally complete. Advanced outfitting reduces labor because it allows workers better access, better working conditions, and often better tools.

Advanced outfitting includes installing a group of components on a common baseplate in a shop away from the ship (on unit outfit); installing components in a block of structure that will later be joined to other blocks (on block outfit); or leaving the deck inverted and separated from the hull, outfitting both with greatly improved access (blue sky outfitting). One simple, but very effective example from BUSL was installing insulation pins on the plate just after it was cut.

Advanced outfit also implies that structural elements related to outfit are cut and erected with the structure. For example, foundations and brackets, even minor ones, are attached as early as possible as structure is erected, and penetrations are numerically cut with the structure. This latter practice most clearly shows the potential improvement. Rather than laying out, measuring and hand cutting an opening in the confined spaces of the ship before running a pipe, a worker merely locates the correct hole (coded with a fiducial mark) and runs the pipe. If the pipe pieces are also pre-cut and bent, he only needs to connect them in the right order and need never even consult a drawing, which potentially reduces engineering costs as well. Nichols [Nichols, 1993] claims that CAD/CAM saves more money by enabling advanced outfitting than by eliminating hand shipfitting.

Group technology is organizing work by processes and problems in manufacture instead of ultimate function in the ship. For example, all piping components of a given material and range of sizes would be classified together even though they were part of different systems, because they will require similar tools and skills to assemble.

Group technology not only brings the correct processes to bear on a manufacturing problem, but also allows parametric comparison of parts accounting for differences in manufacturing difficulty. Time and cost records keyed to part classification as well as quantity greatly improve accuracy in scheduling and cost estimating. Ultimately, analysis of these records may also improve standardization, by reducing the number of different components in use and by recognizing opportunities to standardize whole systems.

Advanced Outfitting/Group Technology is only possible by using accurate geometry, which is provided by the product model and the accurate structure produced by CAL/NCC. The product model also allows a clear understanding of the structure and how it is constructed. Thus, it can be used to determine optimum (or even possible) methods and sequences for outfitting.

Piping, machinery and joinerwork software has to be integrated with CAL/NCC. Yards must also change outfitting, construction, and even design processes to make the most out of these techniques, and can use the data in the product model to classify work products into groups.

One interesting example of design for outfit involves blue sky outfit. Since outfit components may have to be inserted between temporary beams in order to maintain the correct hull shape, this works better with a more open frame spacing than might be optimum for weight. The BUSL was designed with a comparatively large transverse frame spacing, six feet in some areas, for this reason.

## **FLEXIBLE STANDARDIZATION**

*“Some assembly required...”*

*Direction often found on children’s toys*

Small builders often serve specialized markets with more or less similar ships. By standardizing details and ship systems, builders can develop a flexible standard product line that can produce a custom ship out of standard parts. CAD/CAM enables standard details, parametric design tools, and classifying subcomponents by work process. Design costs are minimized, workers are always advanced on the learning curve, and bidding, weight estimates, and scheduling are much more accurate.

Group technology/product classification is one of the keys to a flexible standard product line as noted above.

Improved, even automated bidding is possible by using standardized components. Munson boats were ordered explicitly by the customer, out of a catalog, standard system by standard system, parameterized as much as possible. As a result, there was a very accurate database of costs available to the sales force and they could generate a computerized quotation in less than an hour - down to a detailed bill of materials.

## **CONCURRENT ENGINEERING**

Concurrent engineering is addressing production concerns simultaneously with end-product functionality, and developing multiple systems simultaneously. The integrated product model is the key communications tool for concurrent engineering.

Typically, the structure is designed well ahead of the

systems. This is not only traditional, but is often driven by the lengthier process required for finalizing the machinery selection. A key to productivity is cutting penetrations for systems simultaneously with structure. Not only is the actual cutting automated (as opposed to being done in difficult conditions within the structure), but the penetrations provide the necessary layout information for the systems, eliminating much measurement. It is worth holding back cutting steel until the penetrations can be added, but this requires a system to return penetrations to the steel designers. This can be accomplished by standardizing origins when geometry is passed from structural designer to machinery designer. Then the machinery designer passes the penetrations only, on a specified layer, back to the structural designer, who then adds it to the steel parts. This can easily be done with blocks or XREFs.

However, the product model facilitates the most important aspect of concurrent engineering – the ability to see the entire space or system at a glance. In many cases, if a designer could see the whole of the space, he could produce a much more efficient design, either for end user functionality or for production. The final product model obviously provides for opportunities to change for the better once it is finished, but this is impossible at the beginning of the project unless the project can be laid out in a structured fashion, much like modern programming. Computer programs are designed from the top down, with dummy or “black box” modules that are only specified at their interfaces, acting as “space holders” in a high level design. Each module is then detailed internally so that it lines up with the required interfaces. The equivalent procedure in ship design is “Right of Way”.

This process replaces the “first in gets the space” process traditional in ship design. Instead, 3D volumes are passed out for each system. As long as the designer stays within the volume, he is guaranteed not to hit anyone else. This not only prevents collisions and allows more rational use of space, it also allows tighter packing, because a designer will not allow unknown and probably oversized spaces between his system and others due to a lack of knowledge of the other systems. Right of ways must be pre-determined by a senior designer, knowledgeable with the requirements of all systems.

## **ADVANCED WORKFLOW CONTROL**

*“The thigh bone’s connected to the hip bone ...”*

*Traditional Southern spiritual*

Advanced workflow control uses the product model, process classification, statistical measurement, and design for production to allow self-scheduling work. The product model also allows part/assembly tracking, semi-automatic workplan generation, and structural assembly

simulation which all improve workflow.

Palletization is dividing work into small kits or virtual pallets containing the parts, information and tools required to do a specific task. A pallet is a collection of upstream interim products that produces a single interim product and passes it downstream. Pallets are organized by the tools of group technology to contain products requiring work processes that are either related by process or location or both. The pallet has to be constrained in time and location, and have work content small enough to be accomplished in a relatively short period of time (a week or less.) If nothing else, a pallet gives the work team assigned to it a clear notion of the required work pace, which by itself speeds up a motivated work force. In addition, a pallet is only open for charges for a short period of time. This prevents the common practice of loading charges from other tasks onto any open, long-term job.

*Kan Ban* is a technique developed by Toyota [Ohno 1978] and means “signal card” in Japanese. The basic concept is that a work package or pallet has a card attached. The card is returned to an upstream process as a signal to prepare another designated pallet. Kan Bans do not have to be cards, however. Bins and even marks on the floor have been used as Kan Bans. A given pallet placed at the CNC machine could be a signal to fill it up with particular cut parts. Kan Ban are most common in production situations where there are relatively few parallel paths, and are primarily suited to smaller ships because the relatively short production time prevents parallel, self paced workflows from getting severely out of step.

The point of Kan Ban is that it facilitates self-pacing work and reduces planning effort on the part of management. Timing is no longer explicitly planned - it is only required that the order of operations be known, to connect the Kan Bans because work is now pulled through the shop instead of being pushed through. The self-pacing of work will almost certainly increase speed, because workers will reduce downtime waiting for work. If they are motivated, they may even increase productivity, perhaps by radical amounts. Workers at Lincoln Electric are partially paid based on piecework. As a result Lincoln workers typically make twice what they would in equivalent jobs elsewhere [Lincoln 1944]. However, costs at Lincoln are half their competitors - so Lincoln workers are **four times as productive**. Piecework per se could even be extended to encourage internal entrepreneurialism. Worker teams could “bid” on pallets, with financial rewards for quality and productivity.

Assembly trees are another alternative form of documentation. In this case, an assembly is broken down into sub assemblies in stages until each stage is simple enough that it requires no documentation (usually

because the parts only go together one way). The workers then just work their way up through the tree until the entire ship is built.

Construction simulation is another tool that is enabled with the product model. The geometry of the model allows simulation of installation of large components, but it also acts as an assembly tree so that the order of construction can be determined. This in turn allows simulation of not only specific installations, but simulation of the entire process.

## STATISTICAL MEASUREMENT

Statistical measurement provides data on the effects of process changes, labor content and timing that drives scheduling, estimating, and continuous improvement.

Part classification is required for valid statistical data. We must be able to compare parts with like process problem features in order to be able to separate the effect of changing a process and inherent problems with making the part. We have to be sure that we are really improving the process, not just making easier parts.

Small pallets with well-defined work content are also critical to statistical measurement and tracking. There are two reasons for this: small pallets will contain a smaller mix of product classifications; and most important, small pallets will not remain open for charges for long periods of time, presenting temptations for “cost leveling” from work packages that are going over budget.

Measurement techniques should be chosen not to be invasive and should be thoroughly explained. Workforce “buy in” is critical to success in statistical measurement, hence it must not be seen as a potentially adversarial tool. One example is using two clocks on each welding machine, one activated when the machine is turned on, the other by application of welding power. The ratio between the two gives utilization factor for welding, with little extra effort on the part of the workforce. However, welders will be suspicious that this is an attempt to spot “goofing off” unless they can be convinced that the goal is for design to accurately estimate welding costs and especially to determine those details and procedures that are easiest for the welders. The latter goal will assuredly get not only accurate information, but excellent feedback on other aspects of ease in welding. Worker involvement is critical to success. The most successful examples of statistical process control in industry have uniformly been those with workers themselves making the measurements and controlling the subsequent use of the data.

## CONCLUSION

While the large shipyards tend to pioneer new technologies and construction process concepts, the savvy small yards will continually find ways to implement those

same ideas. Eventually, the small yards that survive will be those that most effectively make use of the large yard concepts.

Jonathan Ross stated [Ross, 1977] that, “While aggressive practices [are] key to ensuring the success of high technology shipyards, those shipyards used CAD/CAM/CIM to gain competitive advantages over low technology yards through approaches such as:

- Development of more complete, consistent, production oriented design packages;
- Earlier project schedule and planning simulations; and
- Improved ability to coordinate design, procurement and production within the entire enterprise (shipyard, vendors, customers, and regulatory bodies)

The authors would like to conclude non-traditionally with a call to action rather than a summary of what we have found:

## CHANGES

Shipyards must change to remain competitive. The YARD has implemented changes that radically affect many workers and begun the journey of continuous improvement with CAD/CAM. This is despite the constraints of Federal Acquisition Regulations, numerous Civil Service rules and a wide range of other limits inherent in its public role. There are many “broken rice bowls” in the shop and in the design office. Nonetheless, the YARD has embraced changes and furthered them, improving quality and productivity. Munson Mfg. tripled its profitability **and profits** within a single fiscal year. Other private shipyards have followed other paths of change based on their needs and opportunities and have been successful as well.

Other shipyards may not need or embrace our particular methods of approaching CAD/CAM, but they should embrace the notions of change, systematic re-engineering and continuous improvement using CAD/CAM as a tool. They work.

CAD/CAM has some very profound effects for design agents. The products and features that shipyard clients desire will become much more varied and design agents will have to invest more time and effort in customer alignment. Design agents must also begin to partner more closely with shipyards. These developments require design agents to know much more about the details of shipbuilding - again, profound knowledge, and much more about process re-engineering. These developments will require wrenching changes as well.

## COOPERATION

Few small shipyards and fewer design agents have the resources to go it entirely alone with CAD/CAM. In

addition, standards development, and interfaces between design agents, vendors, regulatory bodies, and shipyards require cooperation. One of the distinguishing features of the PC CAD industry as a whole has been the high level of cooperation between users. Users and user groups have made countless routines and other valuable assets available for free and have been exchanging tips and training since the early days of CAD. The shipbuilding community should embrace this model and institute processes for interchange of CAD/CAM information specific to shipbuilding. We will all benefit.

### Notes:

*The views expressed herein are those of the authors and are not to be construed as representing the views or official policy of the Commandant or of the United States Coast Guard.*

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## ACKNOWLEDGMENTS

The authors would like to specially acknowledge the engineering staff, shipfitters and welders at the Coast Guard YARD and Munson Mfg., Captain Hested, the late Captain Gonski, and Commander Turner, also of the Coast Guard YARD, Gene Galipeau, Eric Jolley and Cliff Estes, and finally Michelle Barry and Mick Kaniecki for their work on the figures.

## REFERENCES

- AUTODESK, "Toward Design Without Boundaries"  
*White Paper*, Autodesk March, 1998
- DEVRIES, R. et al, ERAM, "A Revolutionary,  
International Approach to Engine Room Design",  
*Maritime Reporter/Engineering News*, Sep. 1997
- DAKAN, M. "Can A CAD System Yield Productivity  
Benefits?" *CADalyst*, November, 1994
- GRIBSKOV, J. Personal Correspondence, Intergraph  
Corp., Crystal City
- JOLLEY E., "AUTOTOOL/DB; A Solution for Ship  
Design" *CADalyst*, Jan 1992
- LOVDAHL R. H., MARTIN, D. J. et al., "The NIDDESC  
Ship Product Model; The STEP Solution" SNAME 1992  
Ship Production Symposium, September 1992.
- LIDDLE, A., "Hot Tip Harry", *CADalyst*
- LINCOLN, J., Incentive Management, Lincoln Electric,  
Cleveland OH, 1944
- NICHOLS, A., Personal Correspondence, Nichols Bros.  
Boatbuilders, Freeland WA, 1993
- OHNO T., *Toyota Production System*, Diamond  
Publishing, 1978
- ROSS, J. "Integrated Ship Design And Its Role In  
Economical Ship Production" *1995 Ship Production  
Symposium*, SNAME
- ROSS, J. "Requirements For A World Class Shipyard"  
*1997 Ship Production Symposium*, SNAME