SHIP PRODUCTION COMMITTEE
FACILITIES AND ENVIRONMENTAL EFFECTS
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EDUCATION AND TRAINING

April 1997
NSRP 0532

THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

1997 Ship Production Symposium

Paper No. 4: Implementation of Integrated CAD/CAM Systems In Small And Medium Sized Shipyards: A Case Study

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

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **APR 1997**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **The National Shipbuiliding Research Program 1997 Ship Production Symposium, Paper No. 4: Implementation of Integrated CAD/CAM Systems in Small and Medium Sized Shipyards: A Case Study**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center CD Code 2230-Design Integration Tower Bldg 192, Room 128 9500 MacArthur Blvd Bethesda, MD 20817-5700**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**20**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS

1997 Ship Production Symposium

April 21-23, 1997

New Orleans Hilton Hotel

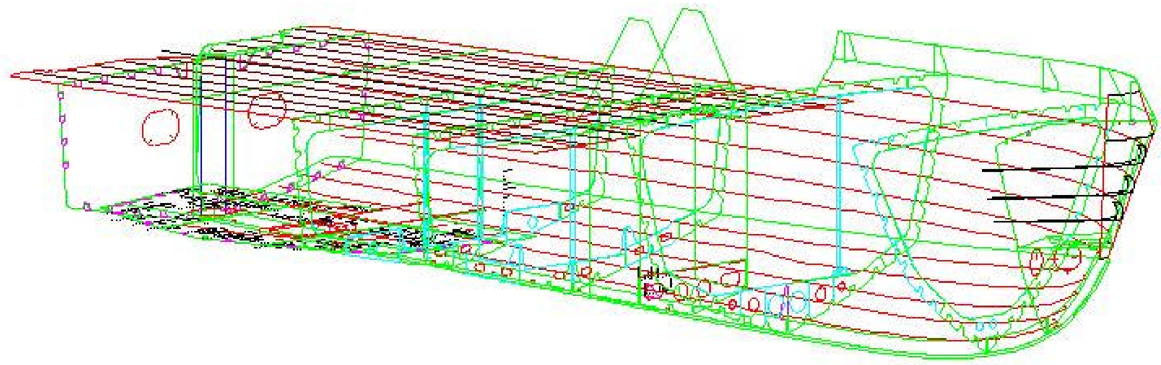
New Orleans, Louisiana

THE SOCIETY OF NAVAL ARCHITECTS & MARINE ENGINEERS

THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS
601 Pavonia Avenue, Jersey City, NJ 07306
Tel. (201) 798-4800 Fax. (201) 798-4975
Paper presented at the 1997 Ship Production Symposium, April 21-23, 1997
New Orleans Hilton Hotel, New Orleans, Louisiana

Implementation Of Integrated CAD/CAM Systems In Small And Medium Sized Shipyards: A Case Study

Larry Mercier (V), **Tracy Byington**, (V), **Walt Senkwic** (V) and **Christopher Barry** (M)
U. S. Coast Guard Yard and U.S. Coast Guard Engineering Logistics Center



ABSTRACT

The Coast Guard Yard in Curtis Bay, MD implemented a PC/AutoCAD based CAD/CAM system and used it to construct a series of 15 M (49 foot) buoy tenders.

Implementing CAD/CAM is primarily a management, rather than technical, challenge. Performance-Based Management Techniques were used to develop the new system as an integrated whole, controlled and documented under ISO 9001. The process was cost-effective, required minimum retraining, was fully implemented in a few months, and was appropriate to a small shipyard building boats, but extensible as required to medium sized ships.

The authors discuss:

1) The use of Performance-Based Management and team-building techniques to help implement the process;

2) The use of process management techniques to document, control and systematically improve the process in order to remain competitive;

3) The process developed, including methods to allow varying levels of operator skill, geometry, weight and interference control, and development of automation techniques;

4) The lessons learned, the results in productivity improvement, and the future path for continuous improvement.

INTRODUCTION

When the authors first started this project and this paper, it was expected that it would involve primarily technical challenges. What we found is that the technical issues were relatively simple and that human issues dominated both the potential problems and the opportunities. This paper is about processes to implement change in general and their results as much as it is about the particulars of CAD/CAM.

Re-engineering For Integrated CAD/CAM

Computer-Aided Design/Computer Aided Manufacturing (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. For example, Computer Aided Lofting/Numerically Controlled Cutting (CAL/NCC) means that the designer is actually fitting steel at the keyboard.

Though shipyards throughout the world have introduced various aspects of CAD/CAM piecemeal as substitutes for manual processes, the greatest improvement in shipbuilding is achieved by improving the interface between design, production, planning, weight control, procurement and logistics support and creating a new integrated environment where the same "keystrokes" that create the preliminary design are used through the entire shipbuilding process. Two important points are keys to increased productivity throughout the shipbuilding process:

First, 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.

Second, Computer Aided Design is a new paradigm in ship design and construction. The authors intentionally use CAD as an acronym for Computer Aided Design rather than Computer Aided Drafting. CAD includes Computer Aided Engineering, because Engineering is a component of Design.

Viewing 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 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 49 BUSL Project

BUSL stands for Boat, Utility, Stern Loading. A BUSL is a small buoy tender equipped with an aft A-Frame. It backs up to a navigation aid, connects it to the A-Frame, hoists the aid, and rotates the A-Frame, placing the aid on the aft deck for servicing or replacement. The 49 BUSL replaces a Fifties vintage, 14M (46 foot) long boat. The new 15 M (49 foot) boat offers improved habitability so that the crew can overnight away from their homeport, twin engines for improved reliability and a hydraulic system independent of the main propulsion engines for improved control.

The 49 BUSL has a steel, single chine developable hull with a raised foredeck over a galley/mess/buoy workshop. A berthing space for four is forward of the habitability space. The deckhouse is on the foredeck and is aluminum with an explosively bonded joint to the hull. The deckhouse has a forward helm station and an aft facing station fitted with a second steering station and controls for the hoist, cross deck winches and A-Frame rotation. The aft deck is lower and fitted with flush tie-down fittings. The engine room is entirely under the aft deck, with a fuel tank separating the habitability space from the machinery space. Main engines are twin 220 KW (350 HP) diesels, and a combined generator/hydraulic power plant provides 20 KW of electrical power and 21 KW (28 HP) of hydraulic power. The lazarette contains the electronically controlled main hydraulic manifold, an air compressor for powering tools, the sewage tank and stowage for deck equipment.

The first two prototype 49 BUSLs were built in Bellingham Washington, but numerous changes were developed during initial operational testing, so that the production boats differ significantly from the prototypes.

This project was the first new construction at the Coast Guard Yard for some years and the relatively small size of the 49 BUSL offered an opportunity to introduce new processes with minimum cost and risk.

PART 1: ENGINEERING THE PROCESS

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 any real productivity improvements the reason is almost always 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 this faster. Even in the best cases, automating existing processes only produces savings in the specific process automated. Often any improvements resulting from automation are more than offset by the cost, labor and training needed to implement the new technology. Additionally, a 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 to be derived from integrating CAD/CAM is in the process design: the design group giving the production shops exactly what they need in the format they need, when they need it. Note that quite often the emphasis, even from the end customer buying the product, is 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.)

CAD/CAM and the ISO-9001 Quality System

Process design is the key to producibility improvements. Because of this, the ISO-9001 Quality Standard, which emphasizes process control, was a big boost to achieving success on the 49 BUSL project. The United States Coast Guard Yard is the first public shipyard, and the first public industrial facility, to obtain ISO-9001 certification. In retrospect, it would have been much more difficult to efficiently implement integrated CAD/CAM at a medium sized public shipyard without the discipline that ISO-9001 invokes. In the context of the CG Yard’s ISO-9001 system a key element of the planning literally involved detailing out each step of the process (and 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 the true 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 provided that communication vehicle.

The real savings to be gained from integrated CAD/CAM technology comes from the impact of the technology on the entire process. 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's "lofting floor" instead of on the production floor.

The key to launching any successful comprehensive process change is thorough up front planning. The CG Yard's 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 at the CG Yard, several quality technology tools were used. Initially, a scaled-down version of the Quality Function Deployment (QFD) planning method was used. In summary, 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 and construction templates and fiduciaries.

One note of warning regarding ISO: shipyards that seek to obtain ISO certification as an end in itself are most likely missing the full benefit. 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 who 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.

ISO Provided A Starting Point To Help Eliminate Suboptimization

The Coast Guard 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 a myopsy 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 suboptimizing mindset, since it requires as a minimum that cross-functional processes, called Management Operating Procedures (MOPs) and Discipline Specific Operating Procedures (DSOPs) be documented. The mere act of documenting important processes brings a great deal of understanding and brings into the open some obvious inefficiencies that were not so obvious before the processes were documented.

Most important, ISO provided a springboard to create a process improvement system. Once the minimal requirements of ISO were met, the CG Yard established a process improvement system which consisted of the following basic elements:

Identify Processes for Improvement:

Initially picking top priority processes for improvement seemed like a trivial task to some managers, because each thought it was obvious which processes needed improvement. But this turned out to be an area of significant disagreement among managers. What actually needed fixing or improving depended one's perspective. Therefore, the CG Yard used a consensus-building process to determine process improvement priorities. A consensus-building approach was used to determine priorities since everyone's commitment and support was needed for the cross functional boat building improvement efforts. Several criteria were used to prioritize processes:

- *Improvement Opportunity*: How "broken" was the process; how much of an opportunity was there to improve the process?
- *Business Impact*: How much impact is there on the business? This factor includes things like how central the process is to the core of the Shipyard's business, how many people are involved in the process and what would happen if this process was performed poorly?
- *Customer Impact*: To what extent did this process impact customers and what would happen in terms of customer impact if this process were performed poorly?
- *Changeability*: How much power does the shipyard have to change the process? For example, processes such as procurement are regulated by the Code of Federal Regulations and difficult to change, so improvement of these processes had low priority.

The above criteria were used to build consensus in order to get the integrated CAD/CAM process improvement initiative into the Shipyard's business plan. This is because some managers saw an integrated CAD/CAM process as a threat, since the efficiencies to be gained through reduced labor-hours would be made in their functional areas. As an aside, this example provides testimony of the need for every shipyard to have a business plan that is backed by senior management.

Managers At The CG Yard Are Process Owners

The CG Yard defines Process Ownership as the assignment of responsibility for how well a process operates, not only within functional areas of responsibility, but how well the process operates in each of the functional areas through which the process passes. Process ownership by a single manager was a key to the success of the 49 BUSL construction project. Ownership of the CAD/CAM process involves not only changing large portions of the way design drawings are produced, but includes integration of the design itself with the fabrication process. The person at the CG Yard with responsibility for making this happen was the CAD/CAM Process Owner. Ownership of the interface between the detail design, numerical lofting and erection process was assigned to the Chief of the Naval Architecture at the shipyard. The CAD/CAM Process Owner had responsibility for how well the needs and requirements of the production shops were met. This required the process owner to gain intimate knowledge of the erection process and then ensure that the full benefits of numerical lofting were brought to bare. Additionally, under the ISO system, the process owner has responsibility for monitoring his/her assigned process to assure it continues to operate in accordance with ISO documentation and without interference from competing functional interests.

According to W. Edwards Deming, one of the Seven Deadly Diseases is organizational churn: the rotating of senior management every few years. This results in senior managers never truly understanding the profound aspects of the organization's processes and the organization's business they lead. Further, a "constancy of purpose" is never established, which is the first point of Deming's fourteen points of good management. As a public shipyard the Coast Guard Yard suffers from this malady since senior management, which are almost all military personnel, rotate every two to four years. Therefore, the benefits of ISO are particularly significant at the CG Yard since ISO requires that a third party verify that in fact each of the functional areas of the shipyard are at least meeting a minimum quality standard with respect to process and document control. Unfortunately, as in many government organizations, some middle managers have learned the dubious skill of being "quality pretenders:" that is, they appear to be committed to the quality efforts without ever really gaining an understanding of systemic management beyond the buzzword level. In fairness, this probably is attributed to the fact that middle managers often perceive they have the most to lose (in terms of power) in crossfunctional improvement efforts. Therefore, a benefit of ISO is that it requires management at all levels to adhere to a minimum level of quality compliance. When all elements of the organization are meeting at least this minimum level it allows those parts of the organization, and those managers who are really committed to the improvement efforts, to move the entire organization ahead.

CAD/CAM and the Malcolm Baldrige Quality Award Criteria

To make the concept of Continuous Improvement (CI) a tangible, institutionalized reality, the Coast Guard Yard is using 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 emphasizes using systemic, systematic approaches to achieve success in key indicators of tactical and strategic results. The CG Yard completed a self-assessment against the criteria in 1993. Even though the CG Yard was in its tenth year of applying quality principles, the self assessment score was less than 160 points out of a possible 1,000. After aggressively pursuing implementation of a performance based management system, the CG Yard was evaluated by third party examiners to be at a score of over 700 points (note that winners of this award score in the 800 point range.). This paper is not about Baldrige Award aspirations but how the MBNQA helped implement fundamental changes to core processes that involved CAD/CAM.

The CG Yard built a management system which linked each of the three levels of measurement using the Baldrige Criteria as the framework: the Organizational Level of measurement, the Process Level of measurement and the Job Performance Level of measurement (i.e., the individual Managers performance appraisals.) Specific numerical goals were then established for each measure and each level of measures and strategies were developed and deployed to achieve these goals. Therefore, managers had motivation through a measurement system to cooperate with crossfunctional improvement initiatives, even if they perceived these efforts to not be in their own personal interests. This approach provided credit and accountability for making improvements, such as cycle time reduction, product/service quality improvement and cost performance improvement. Initially, it may seem unnecessary for such a system to be deployed, since it can be rightly assumed that all managers want to see the shipyard succeed. However, because of the job shop organizational structure, the responsibility for success and improvement of cross functional processes had to assigned to individual managers- and this success had to be measured and aligned with the strategic direction of the organization. Managers find it very difficult to break the suboptimizing mindset unless they are given additional incentive to do so. For example, key managers within the CG Yard saw the implementation of an integrated CAD/CAM system as a threat, since the new process meant that many less labor hours, within their divisions or shops, would be needed. To prevent this, Quality Management Boards, comprised of all senior managers, made these important decisions through the business planning consensus process. Additionally, using the Baldrige Criteria as a roadmap, a system was established in which core processes were systematically selected for improvement, managers were assigned ownership and held accountable for improvements which were determined through measurement. Without this institutionalized approach to continuous improvement it is doubtful that a public shipyard would ever be able to make the improvements needed to stay competitive.

The Key to CAD/CAM Success:

> *"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."*

One of the most important responsibilities of the CAD/CAM process owner is to gain profound knowledge of the erection process in order to assure that detail design drawings fully incorporate the 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:

- obtaining a clear understanding of every aspect of the fabrication process;
- drawing out from production personnel exactly what those design aspects that will promote efficient fabrication.

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 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 at the same time involves a degree of technology that can be fairly challenging to explain to upper management and non-technical personnel.

THE CONTINUOUS PROCESS IMPROVEMENT MODEL

Figure 1 illustrates the basic approach used for implementing process improvement. The first phase basically involves documenting the process and getting rid of the "obvious" waste. The second 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. Phase III 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 Phase III is

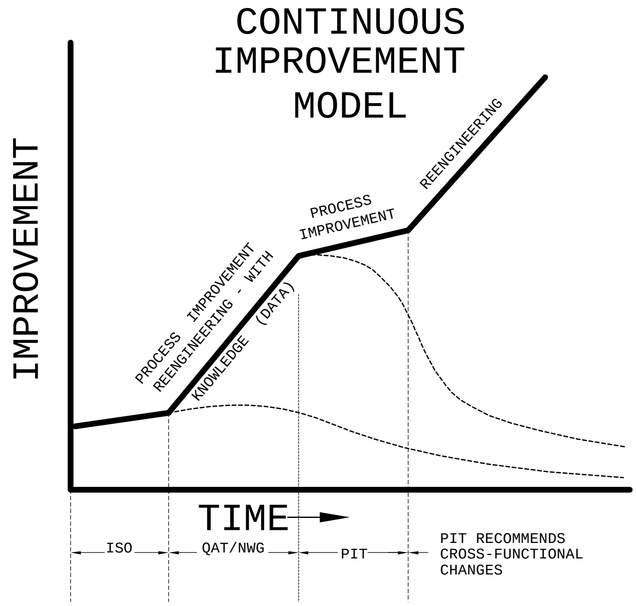


Figure 1

accomplished, the stage is set to actually re-engineer the process.

Organizations fail at process reengineering 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 Dr. 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 so that the significant risks that accompany process re-engineering (which involves massive process change) are mitigated. However, when organizations try to re-engineer processes that are barely even documented, disastrous consequences usually result and the reengineering effort degenerates to little more that a very poorly planned reorganization.

The thin lines in Figure 1 indicates 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.

PHASE I: The "ISO" or Process Documentation Phase

Phase I is the Process Identification and Documentation phase shown in Figure 1. The CAD/CAM process was institutionalized using the existing ISO Quality System, with basic process documentation, and process ownership assignment. The first step in this process was to document the process as it currently operated (without fully integrated CAD/CAM.) Some time was spent finding out how leading shipyards and marine engineering design groups perform integrated CAD/CAM. The industry leaders in this process were identified 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. Related processes included weight management and purchasing documents (bills of materials) development.

Assemble a Cross-functional Process Improvement Team

At the beginning of the implementation of integrated CAD/CAM, the CG Yard loft shop was separate from the Shipyard's engineering design division. In keeping with U. S. shipyard tradition, these work groups were barely on speaking terms. However, since participation, cooperation and commitment were needed from both the design and loft functions and the ship fitting shops, a cross-functional team was established which included players from each of these areas. Team building was emphasized during this time and some time was invested in team building training, such as concurrent engineering training.

Establish Project and Team Objectives and Goals up Front:

Successful process re-engineering requires identifying the key requirements of the overall process. Since the CG Yard is a public shipyard, objectives of the re-engineering process were to:

- Optimize internal and external customer satisfaction by systematic aligning with the customer's desires for ease of use, timeliness and certainty;
- Minimize costs while optimizing product quality;
- Provide a consistent, documented, repeatable level of quality, especially regarding 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 a contract requirement but fail to provide added value (frequently a result of obsolescence caused by the CAD/CAM technology) eliminate them via the Engineering Change Proposal (ECP) process;
- Automate CAD processes where appropriate using CAD macros and programs;
- Identify and prioritize opportunities for improvement by establishing a detailed plan for implementing changes.

<u>Build The Team Dynamic.</u>

Of all the factors that led to the success of the 49 BUSL Construction Project, building a healthy team dynamic was probably the most important. This is probably the most neglected aspect of implementing new technology. During the early stages of implementation, it quickly became evident that trust among team members was a fundamental ingredient that was missing in the initial CAD/CAM process team dynamic. The newly formed team was understandably concerned with job security, or jobs disappearing as a result of implementing a more efficient CAD/CAM process. A key to success was a commitment on the part of the process owner that no one would lose their job as a result of implementing CAD/CAM. Traditional loftsmen were given the assurance that they would be cross-trained to perform not only numerical loft functions, but engineering and design work as well.

<u>Establish Partnerships Between the Shops</u>

Trust and healthy interpersonal dynamics were established on the CAD/CAM team using a method gleaned from the construction industry: mutual goals were agreed upon and basic rules of interpersonal conduct were established. Although this was done informally for the CAD/CAM team, 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 importantly, 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.

<u>Document the New Process With Expert Help.</u>

Once the cross-functional team was assembled and operating, expert guidance specific to the Shipyard's equipment, physical plant, in-house expertise and specific to the 49 BUSL Boat Construction Project, was obtained. Two full days were spent with a subject matter expert mapping out the CAD/CAM process in exacting detail. During this phase detailed work instructions were developed which documented the critical steps of the CAD/CAM process right down to the key stroke. Additionally, each designer and lofter received one-on-one training to ensure there were no misunderstandings regarding what was required. As little as possible was left to chance. If it was thought of, it was discussed and documented. An informal, scaled down version of the Quality Function Deployment (QFD) method was used to catalog interim products and product features. The net effect was that this approach enhanced understanding, provoked communication and provided the baseline upon which to make very specific improvements. Additionally, integrated, internal, focused CAD training was critical to obtaining improved productivity. CAD training from general sources such as community colleges has value in initial implementation, but success came from providing very specific, targeted training just as it was ready to be applied.

Phase II: Process Improvement

Phase I of the CG Yard's Continuous Process Improvement model involved simply documenting existing processes as they currently operated. This was done for the CAD/CAM process to establish a baseline. However, since integrated CAD/CAM was a new process, this phase involved simply identifying in fairly broad terms what had to be done to change from a traditional lofting process to a full blown integrated CAD/CAM process. The method for accomplishing this is called "Boxing the Process", but in short, it consisted of assigning responsibility to specific individuals for fleshing out the details of each step in the new process.

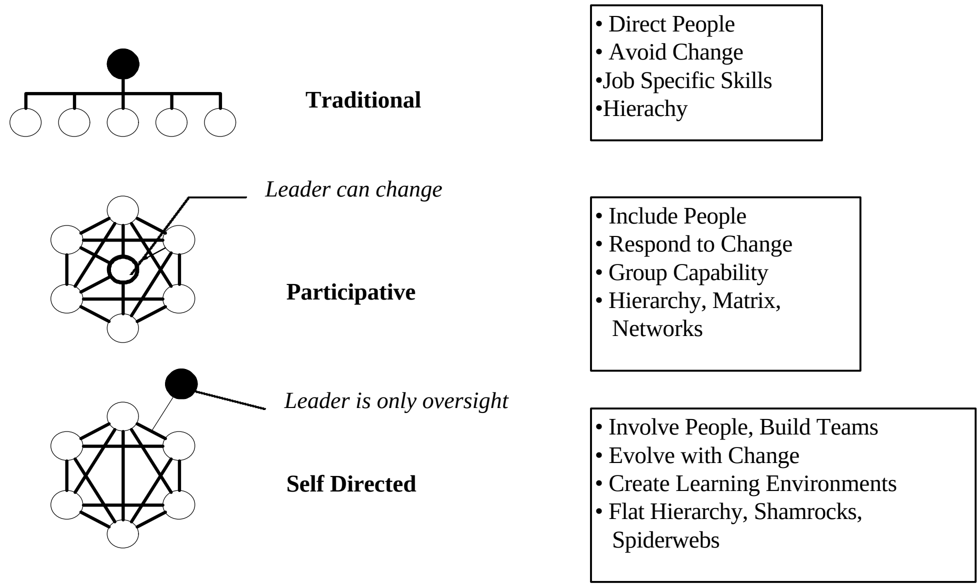


Figure 2

Phase III: Process Measurement

Since this was a new process, this phase essentially consisted of measuring the specific lofting costs and detail design development costs against shipyards and marine engineering companies that are established leaders in integrated CAD/CAM technology. Once the major players in CAD/CAM were identified, it became a matter of gaining understanding of what they do and how they do it, and how to adapt it to the Shipyard's culture and level of technical expertise.

- The measure that was used for initial estimating and competitive comparison was *Pounds of Lofted metal per Labor Hour.* Performance targets for this measure, based on comparisons with other NC lofters, ranged from fifty pounds of lofted steel per labor hour to over 150 pounds of lofted aluminum per labor hour. (This variance is partly due to plate thickness and other effects of vessel size, but is also indicative of opportunities to improve design productivity.) For estimating purposes, the number of plates (steel or aluminum) that will be required provides a relatively good rough estimate of required loft hours. However, more meaningful comparisons, which partly remove the effect of part and boat size, are provided by the following measures:
- *Labor hours per square foot of molded surface (or lofted area.)* This is an easy number to know after the lofting is complete, since CAD macros can automatically track this number. A competitive performance goal for this measure is about 20 square feet of unburned per labor hour.
- *Perimeter Feet per Labor Hour (Length of burn path per hour).* A competitive number for this measure is about 25 feet per labor hour.

Phase IV: Process Reengineering

The heart of successful process re-engineering is proper selection of the cross-functional team structure and team management. The type of team structure that was used to implement CAD/CAM was flexible and was changed to suit the rate of success and progress the team experienced while implementing the new process. Three of the five basic types of team structure were used:

- Traditional;
- Participative;
- Self Directed.

These basic team structures are shown in Figure 2. In brief, the traditional team approach involves minimum risk but also limited potential for creativity and breakthrough. Creative potential increases as team structure moves from traditional to participative, to self-directed; but so does the risk.

For the 49 BUSL, there was minimum tolerance for "emergent outcomes" (i.e., no room for failure.) It was widely believed within the Coast Guard that if the 49 BUSL project was unsuccessful in terms of cost, schedule and craft performance, most likely the CG Yard would be closed. Therefore, the initial 49 BUSL design team structure was a traditional structure. Process features that were absolutely crucial were not debated or consensed upon. The team was directed and held accountable for proper implementation. Traditional roles of team leader and team members were established; the team leader provided specific direction regarding software selection, training requirements, a basic outline of process steps, time constraints, individual responsibility and accountability for results and coordination and communication between the key functional elements. Once these constraints were met the team quickly moved to a participative structure, in which a limited amount of decision-making through consensus was permitted, with the team leader retaining authority to make overriding decisions. The team leader continued to coordinate the group's interactions but retained authority and accountability for decisions. Team members for the most part found this authoritarian structure acceptable as long as the structure was defined up front and it was clear which decisions would be reached by consensus and which were subject to the team leader's final decision.

Synergy occurred when the team experienced initial producibility successes and an attitude of cooperation and coordination became firmly established. This level of team maturity allowed the team to move towards a self directed structure and became a truly energized team. With this structure the team was able to make decisions for itself and take appropriate risks to try new applications of CAD/CAM on different aspects of the project. The individuals began to further refine their own roles, identify problems and opportunities for themselves and were fully accountable for their decisions. The role of team leader became one of oversight. Actual team leadership became variable and informal in that different team members stepped forward at different times to lead the team based on specialized technical expertise and ability, personal leadership strengths, and individual temperaments and energy levels. During this period, major breakthroughs impacting efficiency in both process and product design occurred.

The most valuable product and process design improvements came from the workers themselves: the persons actually doing the CAD/CAM work originated the truly significant breakthroughs that achieved real savings and substantial improvements in product quality. The traditional management approach would never have produced these savings. The workforce achieved these results in spite of mistakes made by senior management on this project. It was the ISO Quality system, coupled with the team design strategy and a commitment to continuous improvement (by senior management) that provided the framework to mine the real gold of creativity and professional expertise that was hidden within the workforce.

During this phase of the project employee job satisfaction dramatically improved, enthusiasm became the norm, employee-originated ideas were suggested and implemented; team members reported how the work had become enjoyable (a rare experience in any shipyard!) These are the ingredients that make a truly productive workforce.

<u>Senior Leadership's Role</u>

The role of senior leadership in implementing the system was significant. Senior leadership established a performance-based management system (management by measurement) and shared in the responsibility for the risk associated with implementing fundamental changes to core processes. Senior leadership did this by giving whole hearted, public support for the changes and by providing the resources needed to ensure success.

IMPLEMENTING INTEGRATED CAD/CAM

The ultimate goal of the CAD/CAM process improvement is an integrated electronic *product model* containing all lofting, structure, outfit, weight and purchasing information in electronic format. It is helpful to note that a CAD file is not a picture; it is a database containing graphic and non-graphic elements spatially referenced to each other. Use of non-graphic, electronically inserted information (called Attributes in CAD software applications) can encode virtually any required information in the model. Traditionally, documentation of ships has been accomplished using paper drawings as the model of the ship for construction. However, this was not always the case. Back when ships were wooden (and men were iron) a three dimensional scale wooden model, or Admiralty Model, was the means of communication between the designers and the builders. The dimensions and other hull defining characteristics literally came right from this scale model. Computers have returned this concept of a three dimensional electronic Admiralty Model. Once again the primary means of communication between designers and builders is the three dimensional Admiralty Model.

Because the model is developed in electronic format, it can be used by all the functions of the shipyard from cutting parts to designing pipe to ordering materials, maintaining logistics records, and palletizing parts for inventory and workflow management of the assembly process. As an aside, this approach can be used for logistics support throughout the lifecycle of boats and cutters. However, development of the conventions and processes for such a model is a daunting task and will require organizations such as the Coast Guard to take a systemic management approach to boat and cutter lifecycle management.

For the shipyard, the areas with the highest, most rapid payoffs were selected for implementation first. This means the steel fabrication, since this area produced the largest immediate gains in productivity. Also, productivity gains in these areas helped create momentum which carried over to improvements in the outfitting, weight management and logistics database aspects of CAD/CAM as well.

During Phase I, the Process Documentation Phase, an outline of the basic eleven steps of CAD/CAM implementation were used to jump start development. This overview helped promote communication among the shops so that understanding and consensus could be built about how to approach and deploy an integrated CAD/CAM system. However, as employees were trained and the process progressed from Process Documentation to Process Re-engineering, the process steps rapidly became quite detailed, with work instructions documented down to the key stroke for some critical process steps.

<u>Develop the Process Overview</u>

The first step in developing the process overview is to identify key inputs and outputs. Frequently this varies between external customers so it is necessary to determine which inputs to the process, such as geometric constraints and drawing conventions, will be specified by the customer and which are left to the shipyard to determine. This is achieved by "boxing" the process as shown in Figure 3.

<u>Align With External Customers</u>

The richness of information available from CAD/CAM adds a new dimension 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. An example of this is data for plate cutting. This data is expressed exactly in the electronic files of the drawings themselves, which show the exact shape and dimensions of all the parts. Additional dimensioning is therefore redundant and adds no value to the construction process. Yet drawing standards for Coast Guard boats require dimensioning which is of no value. An another example: end users usually need drawing data organized by system oriented classifications whereas the builder may needs 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 the these needs to be systematically addressed.

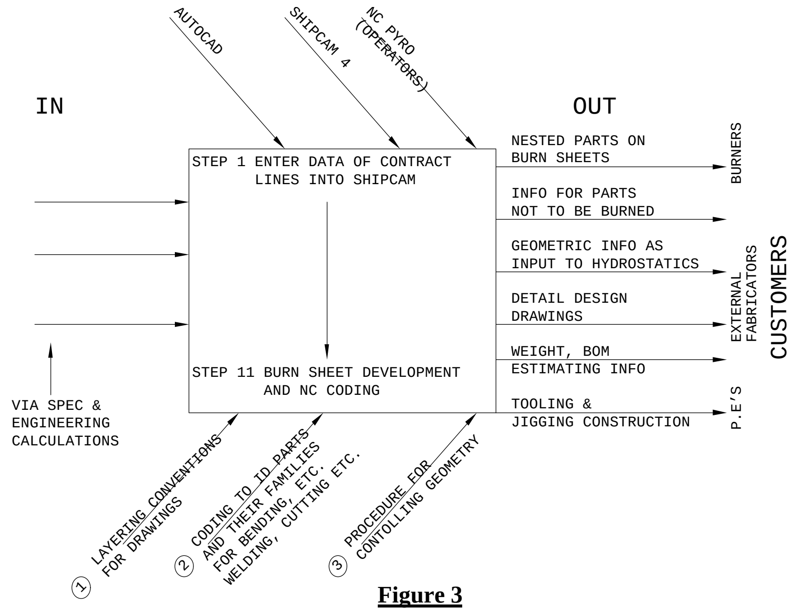


Figure 3

This process of alignment with external customers was not 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 CG Yard processes. In turn, this would have allowed modification of the drawing and other data requirements to streamline design and still retain the value needed for the operators. As a result, the CG Yard produced drawings in conventional 2D format, organized by Ship's Work Breakdown System. This requirement had negative impact in that unnecessary drawings and drawing features were developed.

Align with Internal Customers

Internal customers and suppliers are essentially those workers within the process. A formal alignment process was used with the production shops and other functional work units to determine internal customer needs and interim product features and functions. This is a critical task because it has a dramatic impact on productivity and efficiency. In order to benefit from CAD/CAM technology, internal customers and suppliers must meet and develop technical and specific alignment throughout the steps of the design and construction process. Alignment here means establishing specific requirements for interim product format, features and functions. An example of a function is specific requirements responsiveness for design changes that were needed after the drawings were released to the shops for production. The CG Yard used an internal response standard of two hours for verbal concurrence from the Engineering department for proposed design changes, with documentation, including electronic and red line markups with a Drawing Change Notice to follow within two working days.

Figure 4 shows the workflow in "swimlane" format which 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.

The introduction of an integrated approach to CAD/CAM must be handled carefully because it is intended to reduce the labor content in building ships. There will be resistance and even efforts to sabotage the new process design effort. However, if it is introduced as an opportunity to improve competitiveness and the workforce feels it has job security in light of the reduced labor hours that will be required by the new process there will be better cooperation. Additionally, the workforce must be given the opportunity to actively participate in the program. This was the approach that was used successfully at the CG Yard. In fact, many of the most advanced and creative suggestions were

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 & REQUIREMENTS, GEOMETRIC CONSTRAINTS, CUSTOMER'S SPEC, STRUCTURAL CALCULATIONS
OUTPUTS: "BURN DISKS" (NESTED PARTS IN ELECTRONIC FORMAT) READY FOR NCC

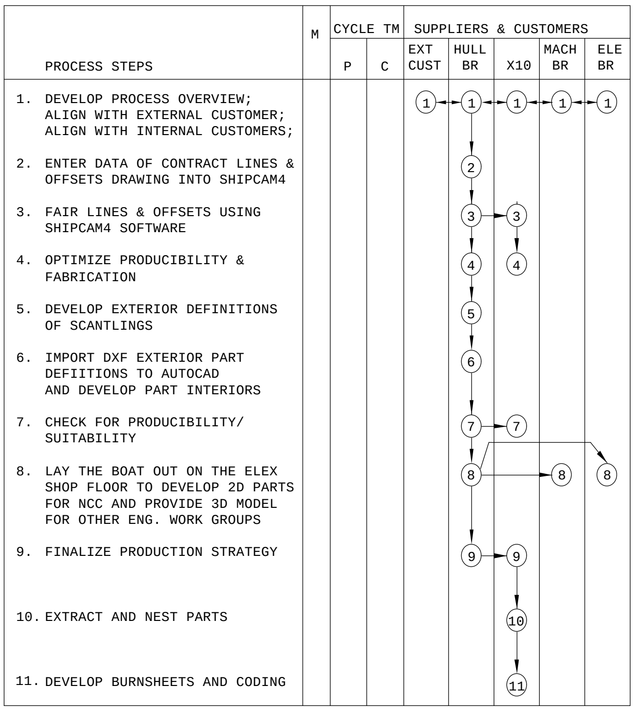


Figure 4

proposed by the workforce, once they were convinced that they were considered a key customer of the CAD/CAM process.

Next, a strawman process flowchart was develop as a starting point. This allowed those assigned to the task of implementing CAD/CAM to focus on the important implementation issues and reduced initial "storming," and confusion.

The design elements are suppliers to the production shop customers. Design personnel must determine the specific needs of the production shops in order to ensure that design is not accidentally suboptimizing the overall process. This requires a formal approach to eliminate overlaps, oversights and non-value added product.

1) The important interim products that design provides to production were identified. For the NCC process the products include:

- Fiduciary Marks or "nick ons," include dimensions, location markings, error proofing markings, part names, numbers and locations, accuracy control markings, reference lines, etc.;
- Generic Torch Code;
- CAD files of the nested plate;
- CAD files of three dimensional parts;
- CAD files in DXF format and
- Text files of offsets.

2) Next, the desired product functions, as stated by the production shops, was obtained. This is called the "Voice of the Customer" (VOTC). The production shops were asked to complete the following statement: "a quality (interim product) is one that is _________." Typical responses were phrases like "easy to use", "timely", "defect free.". Interim product features were obtained in a similar manner. The production shops were asked to complete the phrase, "A quality (interim product) is one which has ________."

3) The 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 5. Fiduciary marks are dimensionally accurate marks placed by automated machinery on the metal itself that depict either information for part alignment or the location of some other part. Coding is text information such as part numbers for the part itself or for fiduciary marks.

4) The VOTC attributes were then translated into precise, measurable Substitute Quality Characteristics (SQCs), product characteristics that were 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 5.

5) The relationships between the VOTCs and the SQCs were then determined. In Figure 5, 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.

6) The SQCs were 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 was then selected. This was the basis for communication between the internal customers and suppliers in the CAD/CAM process. This process therefore quantifies and prioritizes the desires of the production shop internal to the CAD/CAM process.

7) Executing the above steps in effect develops the first matrix, shown in Figure 6, of the four Quality Function Deployment Matrices, Figure 7. 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 provides great value in zeroing in on what is truly important and

PRODUCT ATTRIBUTE GROUPS	VOICE OF THE CUSTOMER	SUBSTITUTE QUALITY CHARACTERISTICS: HOW MANY MANHOURS ARE SAVED SORTING THE PIECE PARTS?	HOW MANY TIMES DO SORTERS/ASSEMBLERS HAVE TO STOP AND 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?
TIMELINESS	SPEEDS UP SORTING, PALLETIZING OF PARTS W/ SIMILAR MANUFACTURING REQM'T	+	-	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 AND 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 5 1

should be addressed first.

Develop the Schedule Strategy

One of the biggest opportunities for inefficiency in the CAD/CAM process that was discovered was differing expectations for schedule and sequence between the external customers and the shipyard. The sequence and rate of construction will determine the order and schedule of part cutting and hence the requirements for the lofting schedule and for manpower. Developing a schedule detailed enough to address these issues was found to save many labor-hours in inefficiency during production.

Construction Strategy

CAD/CAM produces extremely accurate parts, eliminates floor fitting and makes elaborate cutting details cheap - "the second cut is free." This provided radical changes in construction processes and strategy. Again, this required specific, technical alignment. Both the Production and the Design functions must have "profound knowledge" of each other's processes, needs and capabilities to find the CAD/CAM opportunities for productivity improvements.

Poke-Yoka, the Japanese term for error-proof part assemblies, provides unique tabs, slots or other features to align parts prior to welding. Part accuracy and elimination of field fitting helped change the order of assembly, making construction cheaper and helped improve advanced outfitting. Tools for assembly were cut along with the parts. All of these opportunities helped to radically improve production. However, this was made possible only because the designers knew what questions to ask the Production Shops, in order to know what to offer.

Data Conventions

Parts cut with an integrated approach to CAD/CAM are assembled, not made, by the workforce. Improvements in the quality of assembly were a significant opportunity for both producibility improvements and in streamlining design. Fiduciary marks are the best example. Fiduciaries were applied automatically with a pneumatic punch and showed alignment marks, accuracy control marks. Since they eliminate hand measurement and layout, they reduced labor substantially and improved accuracy. Fiduciaries also were used within the design drawings in lieu of some conventional symbols thereby eliminating non-value-added drafting labor. Other alternative data conventions included assembly drawings and jig setup tables- these provided significant productivity improvements.

PART 2 - THE PROCESS

The integrated CAD/CAM process eventually used for the 49 BUSL project differed from that originally envisioned. This showed the importance of using the TQM approach. Had the initial process been simply imposed based on the wisdom of upper management or a consultant, the project would have suffered greatly, but because flexibility and a team organization and consensus approach were used, a realistic, efficient process was developed from the initial one envisioned. For example, management initial envisioned using full three dimensional solid modeling. However, the workforce developed hybrid "2-1/2 Dimensional drawings." These drawings were essentially 2-D, but through the maintenance of the User Coordinate System (UCS) discipline, 2-D drawings were properly oriented and located within the 3-D wire frame model. This helped eliminate expensive training and schedule impacts that would have been caused by the lengthy time it takes to become 3-D proficient.

Software

The Coast Guard has been using AutoCAD, now Release 12, as its official CAD standard since 1990. Lofting software and the process for lofting had to be compatible with AutoCAD and had to operate on the existing available workstations, principally DOS based 486 or Pentium PCs. Use of PC CAD applications in shipbuilding is somewhat controversial, because it does not lend itself well to production of an integrated product model in the fashion that integrated, dedicated packages do. However, the Coast Guard is moving towards such a representation, but has not yet implemented it, so this was not important for this project. In addition, the use of linked PC CAD drawings and databases has been successfully used in the petrochemical process industry and other facilities management activities to produce a product model that consists of many related files rather than a single model. In the long run, the authors believe that this approach will suffice for

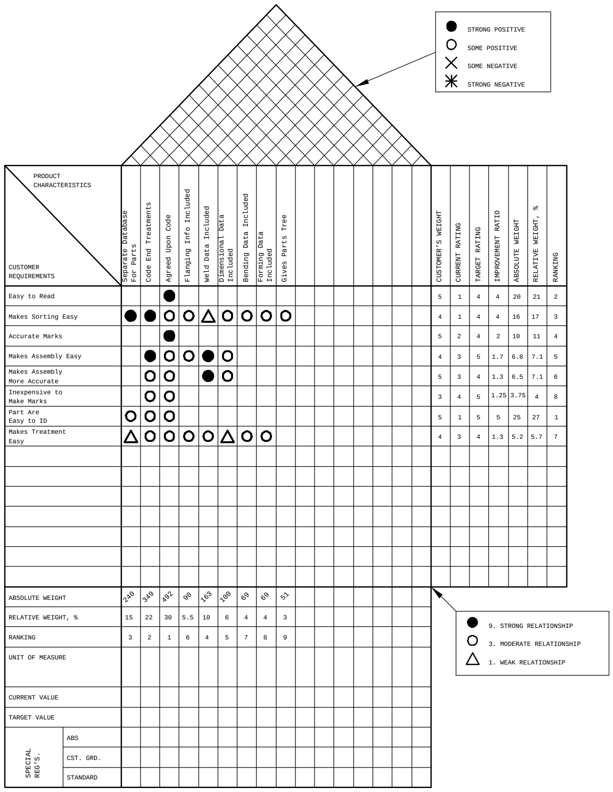


Figure 6

the Coast Guard and small ship and boat construction as well.

ShipCAM4 fairing and lofting software was chosen mainly because of it's orientation toward shipbuilding vice design, its cost, and its compatibility with AutoCAD and the existing workstations. The program offered numerous construction oriented features that were seen as necessary for long term use. ShipCAM has features that facilitated 2D drafting which turned out to be useful, though this was not initially appreciated. ShipCAM has a companion program for generating CNC code from drawings of the nested plates. This program added torch lead-ins, lead-outs and the tool paths automatically, so it produced labor savings in NC coding as well. One other advantage is that this software has only a single station license, so that there is no possibility of multiple models of the molded geometry being developed, which would cause the loss of geometry control.

Numerous AutoLisp routines were used which facilitated particular tasks, notably layer management and weight extraction. These routines were obtained from a combination of public domain sources, by programming in-house, or from a consultant firm specializing in numeric lofting. The consultant provided both their own routines and custom routines developed to the needs of the shipyard. The re-engineering process identified those areas of greatest value to automate and the cost of developing and purchasing was paid for many times over. Also, the numeric lofting was found to dramatically improve productivity of not only the lofting, but the designing as well. For example, the drawings that were provided by the customer to the shipyard had an unorthodox layering convention unsuitable for geometry control and NC lofting and cutting. CAD macros were used to properly layer the drawings to suit the CAD process. Another example included the problem that the initial contract guidance drawings that were provided to the shipyard were a mix of open and closed polylines. Macros were used to place the drawings in an editable format, then convert them to required polyline format for NCC.

2D - 3D

The generic method for computer lofting is to model the entire ship structure in 3D, then to subsequently extract the piece parts and flatten them to 2D, nest them and generate CNC code. Our initial plan was to follow this approach, with each designer working on specific major structural components, then assembling the entire boat from the components. There were several obstacles to this approach at the time the process was initially developed.

First, a simple 3D model would not provide the required documentation for the end user in the conventional format. AutoCAD provides a facility called "Paper Space" that allows a drawing to be built from 2D views on a 3D model and is a partial solution. However, the only way to control visibility of overlapping levels of a 3D model is to assign them to different layers. However, the CNC coding program has different layer naming conventions to distinguish between inside and outside cuts, marks, text, and extraneous (for the torch) information. This conflict can be resolved readily enough by a combination of layer naming conventions and software to rename layers during the transfer process, but with all the other demands, the schedule did not allow the time to develop and implement such a system. Using paper space also is initially confusing, and required more training than there was allowed by the schedule. Second, working in 3D in AutoCAD without any add-ons is somewhat cumbersome and requires additional training and experience. There are numerous add-ons ranging from major software to small utilities that improve 3D performance, but these also require training. Third, experienced designers are very comfortable in orthographic drafting. Finally, there are a substantial number of components that are not represented as required for manufacture in 3D, notably shell plate. Since these components have to be flattened to 2D eventually, the advantage of using a 3D model is diminished.

However, the value of a 3D structural model for visualization, accurate geometry generation, interference checking, and weight management are so significant that such a model had to be developed. Therefore, a combination of 2D and 3D processes were used as an expedient for this project. In retrospect, this may in fact be the most practical solution to the problem of the currently prohibitive costs associated with full blown 3D solid modeling. This approach also controlled the configuration as required by ISO and ensured that all designers were using the correct data.

The designer with the most 3D experience was ordained the "Geometry King." He maintained the ShipCAM database and gave other designers correctly oriented, properly UCS'ed 2D geometry of the molded surfaces derived from the ShipCAM model. The facilities for extracting 2D as opposed to flat 3D geometry provided by ShipCAM meshed well with this approach. Each designer then 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 then placed them in the 3D model in their proper orientation for interference checking and

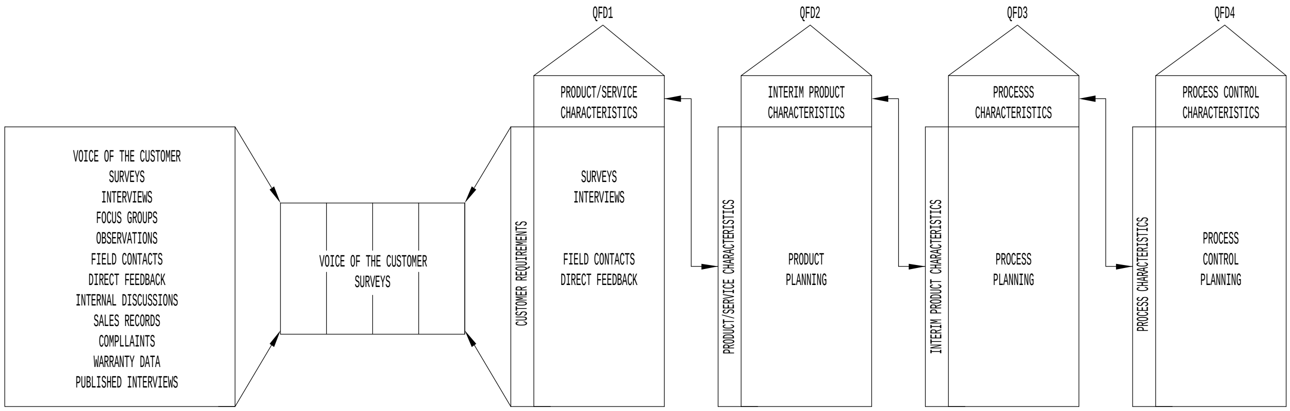


Figure 7

configuration control This process was actually very simple and effective.

The key to easy reinsertion of the parts and control of designed geometry was the 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 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.
small compared to the loss of productivity from

All-in-all, the use of this hybrid "2 1/2 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 designers uncomfortable with 3D. Most important, this process has provided a bridge to 3D and Paper Space. The deckhouse was designed and detailed in full 3D and presented partially in Paper Space, and many of the designers had experimented with 3D or paper space in part most of the drawings by the time the structural design was complete.

<u>Weight Management</u>

The 49 BUSL is a low speed steel workboat, but because of a combination of maximum freeboard limits for the working deck and damage stability and draft limits, it is relatively weight critical. CAD/CAM provides extremely accurate weight data because "what you see is what you cut" and all cut parts are fully detailed. The 49 BUSL design effort allowed integrating CAD, the weight manager's database and the Bills of Materials for purchasing. This greatly reduces both the time AND the mistakes that occur from multiple data entry.

Each part was attributed with a "partinfo" block by the designer, who input the type, thickness, and other aspects of the material. The designer then ran an AutoLisp routine that calculated the area properties and center of gravity of the part using data from the previously preserved attributed origin block. It then automatically inserted this data in the partinfo block as attributes. The weight manager subsequently extracted them from each drawing's file to a database management program.

This process considerably streamlined development of Bills of Material and will be used for future generation of Integrated Logistic Support data.

PIPING AND OTHER OUTFIT

The 49 BUSL project did not use as extensive or tightly integrated a process for piping. There are several reasons for this. The CG Yard had no specialized software for piping analogous to ShipCAM; the piping would not be fabricated with numerically controlled machinery; the piping systems for such a small boat are very simple; the federal procurement regulations delay critical design information for most of the major systems. However, the main benefit to piping provided by CAD/CAM was still achieved. That is the ability to incorporate outfit oriented features in the initial structural cutting. A process to feed back penetration and integrated structure, foundation and bracketry data paid off handsomely. Additionally, interference checking became a realistic, systematic and highly accurate process.

The same system was used for providing backgrounds for piping, electrical and other outfit once the structure was firmed up. Each designer requested specific molded geometry or structure from the Geometry King and used it as background for his efforts. Since the structure geometry was absolutely accurate, this saves considerable effort, improves accuracy and eliminates structure/outfit interferences. Additionally, there is a cascading benefit which allows virtually all potential piping to piping, piping to electrical and ventilation potential interferences to be efficiently eliminated. When the systems were designed in 2D, the penetrations and similar structural interfaces were returned to the Geometry King, incorporated into the structure, and CNC cut.

The 2-1/2D approach to design development was also effective in eliminating interferences. In boat and ship design, interferences that are not caught until after the drawings are released for production and construction represent some of the most costly waste. When extensive rerouting and redesigning of piping and outfit arrangements is done on the shop floor, any benefits that could have been gained by CAD/CAM and careful erection sequence and scheduling planning are completely lost. When this occurs, scheduling pressures become the overriding concern, a free for all to obtain the easiest installation locations occurs among the shops and configuration control is lost. However, because the UCS discipline was maintained on this project, interferences were eliminated from the production drawings before they were released for production. An "Interference King" was given responsibility for preventing interferences. The Interference King used a 2 1/2 D composite drawing approach, which proved to be a cost effective method and much less expensive than trying to develop a full 3D model for interference checking. By way of background the shipyard had experienced poor results on past major renovation projects trying to use composites to prevent interferences. In retrospect, the reason that these early composite drawings failed to produce any real economic benefit were two-fold: (1) the background structure had to be used as reference to locate the new installations. This created huge, unmanageable drawings sizes when these various drawing were brought together in one composite; (2) the background structure was not accurate enough to be used as exact construction location references since the true (lofted) geometry was never incorporated into the detail design drawings before the new integrated CAD/CAM process was deployed. However, with true geometry drawings and the use of the User Coordinate System (UCS) discipline (in which the exact locations of everything is maintained) both of these problems were eliminated. For example, when checking for potential interferences with bulkhead piping penetrations generated by four or five different piping designers and a couple of electrical designers working in the same crowded areas, the following method was used: each designer was given a zone within which to work. Next, when the potential interferences were placed, the designers notified the interference king, who then blocked *only the penetrations* into the composite drawing. Instead of importing each entire drawing into a overall composite, just the several penetrations were "W blocked" and down loaded from their source drawings via the designer's CAD network. This approach was made possible because the exact x, y and z location of the penetrations were known and kept current with the (0, 0, 0) point of the vessel. The same approach was used to place and check for interferences of equipment and foundations. This approach allowed up to about 18 designers to work simultaneously with good coordination to meet production schedule demands.

PART 3: RESULTS

The results for structural erection were very good. Implementation of this integrated CAD/CAM process has resulted in structural construction cost ***underuns*** of over 25 per cent. Additionally, there were virtually no bad parts and erection, particularly on the second hull, when the shop had accepted that the parts would really, truly fit, went very rapidly. It is difficult to determine how much time was saved, because it had been some time since any new construction was done in the shipyard and there was no readily comparable data. However, and perhaps more important, the process, and therefore the CG Yard as a whole, was viewed by the prime customer as successful in this phase of the project as illustrated by the following quote from a memo written by RADM North, Chief of Acquisitions for the U. S. Coat Guard, the customer of the 49 BUSL project:

> *"I am especially impressed with the producibility improvements the CG Yard has implemented in order to build the buoy boats as efficiently as possible. The extensive use of computer resources for lofting and three dimensional modeling was particularly impressive and shows the CG Yard is effectively managing the leading edge of boat building technology."*

INNOVATIONS

The most surprising outcome was the spontaneous improvements generated by the workforce when the process became successful for steel. The team dynamic became an important factor, with many of designers and production personnel actually commenting that the work had become enjoyable. Because of this, the effort to find producibility improvements was championed by the designers and production persons. The following few examples illustrate that the most important factor impacting producibility is workforce moral, since the most important improvements were made by the designers themselves and not by management.

Structure and Joinerwork and Foundations

The designer responsible for joiner work independently developed a process to CNC cut all of the joiner panels, saving substantial labor hours. Also, features for rapid assembly based on Ready-To-Assemble (RTA) knockdown furniture concepts were incorporated. The designer then developed an integrated joiner foundation concept to support the panels and designed and numerically cut a jig to allow precision assembly of it.

Another designer championed the use of construction jigs for the habitability flat, the web frames, the transom and the bulkheads which resulted in substantial overall savings.

Piping And Machinery Composites

One of the piping designers independently proposed, developed and implemented the procedure for making composites of all the machinery, electrical equipment and piping based on the structural origin preservation procedure. This procedure was then extended so that it semi-automatically generated composites using the AutoCAD "external reference" (XREF) facility and the CAD network server. This procedure reduced interferences and improved arrangement planning, but more important, since it was developed spontaneously by the main users, it fit their needs much better than a system imposed from above and was rapidly embraced. Thus, configuration is better controlled and interferences were virtually eliminated This system also increased enthusiasm for a move to 3D modeling. In fact, the last piping system developed used a quasi 3D process as a trial.

Deckhouse

By the time the deckhouse was developed, the designers were more comfortable in 3D, so they decided to develop it in full 3D using Paper Space techniques, including exploded assembly drawings. The sheet metal shop had been so impressed by the results they had seen in structural steel that they approached the designers to develop a full set of jigs to fabricate the deckhouse as well as the parts themselves. This approach not only improved production, and accuracy but helped to control distortion. The shop and the designers also set up predetermined standard details for the stiffeners, (which were rectangular hollow tube) in the deckhouse, acting as a self-directed team. As a result, the deckhouse is extremely fair and smooth, even though it is 1/8 aluminum. It was also built very quickly.

LESSONS LEARNED

The most important lesson from this project is that the critical issues in CAD/CAM are not technical but procedural and people issues. By empowering the designers and shop personnel to use the new technology to fit their needs, and by building a unified team, their energy and creativity was harnessed in a fashion that would not otherwise have occurred.

Fiduciaries

The use of fiduciary marking proved to be as big a savings as numerical cutting itself, provided that the shop's needs were met by the marking system. The initial alignment process invested significant effort to coordinate the requirements for marking, the most useful alignment marks and mark conventions and symbology. The result was that most of the measurement needed for assembly was eliminated which not only improved accuracy and reduced the chance for error, if saved considerable time on the shop floor. It is worth noting that the few assembly problems were all related to insufficient marking.

Templates

Initially, the shop was to develop all of their own templates, and design was only involved in part production. However, as alignment and the project itself progressed, the shop requested more and more templates such as the house and habitability flat jigs discussed above. Jigs were also produced for pre-fabbing the engine foundations. This proved to be another significant source of improved producibility. The low cost of producing relatively complex jigs improves accuracy substantially as well as speeding production.

Roll Sets

Roll sets are specialized templates used for guiding the roll and press operators in bending components. There were several parts that had to be re-formed. This occurred because traditionally the shop would have produced their own roll sets off of loft data at the same time they made the parts. Because they did not have the traditional information they were used to, they sometimes incorrectly rolled a part, or misused the template data they were given. Design found itself producing more roll templates as the project progressed, but often found that the information given the shop as to how to align the templates was deficient. This is an area that requires a great deal of effort to foster clear communication. Fortunately, very little time was lost in these incidents, but this is strongly attributable to the team building that occurred early on. There was no occurrence of the "blame game" that would be traditional, and each incident was resolved in a couple of hours.

ECNs

One of the most important improvements was in the flow of Engineering Change Notices from the shop to design. ISO requires that the drawings always match the boat, so that the shop could not fix errors on the floor without the concurrence of the designers and without documenting the change. However, the shop was traditionally reluctant to ask for ECNs because of delays. Design therefore made a commitment to get a reply to change requests or problems within two hours or less. As a result, the shop not only followed the ECN procedure fully, but used the drawings more carefully. Maintenance of this discipline saved over 4000 labor hours since it completely eliminated the need for as-built drawings, since the detail design drawings *were the as-built drawings by virtue of the ECN process*. However, even this substantial savings pales compared to the savings achieved in production itself through a disciplined approach to configuration control, which translates into interference control and prevention of suboptimized location of outfitting.

Developable Surfaces

Lines fairing is an emotionally loaded issue in a shipyard. The loft regards fairing as their sole domain and guards this prerogative jealously. As a result, the loft did the initial hull fairing and passed the first molded surfaces to the Geometry King in design.

The 49 BUSL is a developable hull form. An exactly developable surface has zero warp, and between two curves in space there is at most one such surface. However, there is often no surface with zero warp possible. As a practical matter, some warp is feasible in real materials, generally six to ten degrees. In this case there are many possible "plateable" surfaces. ShipCAM has controls on both allowable warp and on parallelity, the allowable angle between two adjacent rulings in the surface, sometimes called "fanning" because it produces fan-like patterns of rulings.

The initial bottom surface created by the loft had very little fanning but lots of warp. When the Geometry King trialled the plates by expanding them as a double curved mesh, they showed some required stressing to fit. Since the stressed areas go red on the display and may require line heating, the plates were said to show “lots of heat”. The loft and design met and decided that there was too much heat in the plates and that new surfaces had to be found, though the chines as faired by the loft would be kept.

When the allowed warp was decreased, the fanning had to increase. This produced an unfair surface where a butt or waterline crossed the hard line at the edge of a fan. This is common in lower speed boats where the chine and keel are not parallel. The solution was to extend the chines and keel arbitrarily aft until the unfair fan was completely off the real hull form. The bottom was subsequently trimmed to the true transom and was satisfactory. However, the team building effort again prevented potential conflicts.

Continuous Improvement

There are many needed improvements in this process. Piping, electrical and machinery must be addressed in the same fashion as structure, so software analogous to ShipCAM has been identified. The 3D skills of the CAD operators need to be upgraded and software aids for 3D are required. Production planning needs to evaluate the opportunities afforded by CAD/CAM to optimize their build strategy. However, the re-engineering process started with this project has successfully institutionalized continuous improvement, so much so that it is now happening spontaneously, and workers are now the drivers of change, rather than management. This is the promised result of empowerment and the most important point of this paper is that it actually works as advertised.

CONCLUSION

Integrated CAD/CAM

The integration of Computer Aided Design (CAD) CAD, Numerically Controlled Lofting, Numerically Controlled Cutting (NCC) and production afford substantial opportunities for improved quality, reduced costs, reduced calendar time and better data collection. However, the key is in fact integration, which in turn requires profound understanding of the entire boat design and construction process and all of the external and internal customer’s and supplier’s interim product features, functions and constraints. NCC can be a source of continuous improvement due to both the improvement of technology and the need to rethink and break down old paradigms.

Approaching CAD/CAM from an integrated process perspective offers is an opportunity to use NCC profitably, but requires careful attention to the principles of employee buy-in, quality management and leadership.

Change

U. S. shipyards must change to remain competitive. Public shipyards in particular have been accused, with some justification, of tenaciously resisting change. The Coast Guard Yard has implemented changes that radically affect many workers. There are many “broken rice bowls” in the shop and in the design office. Nonetheless, by applying TQM principles honestly, the CG Yard has embraced these changes and furthered them, improving quality and productivity. Other shipyards may not need or embrace our particular methods of approaching CAD/CAM, but they should embrace our methods of instituting change and continuous improvement. They work.

ACKNOWLEDGMENTS

The success of structural CAD/CAM in this project would have been impossible without the skills of the production workers, particularly their ability to weld with very little distortion. Joe Schoolden, the Composite King, deserves special mention for taking initiative and implementing the composite control procedure. Eric Jolley, of Elliott Bay Design Group, provided much of the special expertise and custom programming that made this project work. Additionally, Michelle Barry deserves credit for the numbered figures in this paper.

Lastly, the authors would like to acknowledge that the improvements that were made at the CG Yard would not have been possible without the vision and leadership of the late Captain Ron Gonski, US Coast Guard. His inspiration and his dedication to the development of the leaders around him will prepare the CG Yard for the challenges of the twenty first century.

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