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The Successful Implementation of Structural CAD / CAM in a Small Shipyard

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Implementing a CAD / CAM system in a small shipyard requires commitment from management and labor, careful selection of each component of the system, an implementation plan, and a somewhat new approach to design and construction. This paper describes the successful integration of a CAD / CAM system into the operations of a previously unautomated shipyard, yielding production man-hour reductions of 40 to 800 percent. The history of the implementation is traced, along with the successes and failures. Each piece of the resulting CAD / CAM system (software and hardware) is described. The effect of the system on issues other than design and construction, such as estimating, scheduling and planning, management and accounting, are also discussed. The experience gained and presented will aid the reader in making intelligent CAD / CAM implementation decisions while, it is hoped, avoiding some of the pitfalls encountered by the authors.

Introduction

PERHAPS one of the most used and overused buzz words in boat and shipbuilding today is "CAD / CAM." Computer-aided design and computer-aided manufacturing, or CAD / CAM, is possibly one of the least understood tools in the industry as well. It is often talked about, dreamed about, and much maligned for creating new problems when it was intended to remedy existing ones.

The promises of CAD / CAM have yet to be fulfilled in many, if not most, boat and small shipbuilding facilities. The reasons for this are many, but perhaps the foremost is the lack of understanding of what those promises really are, and how they can be applied in a given yard.

Why has it taken a design and manufacturing tool whose development started more than 30 years ago so long to make its way into small shipbuilding on a large scale [1][3]? Few industries are in a better position to make CAD / CAM pay off. There are real reasons, among which are a lack of understanding of how to implement a system, the mistaken belief that CAD / CAM cannot be made to pay for itself, and often inertia (that is, "We're making money doing it manually, why should we change now?").

The first reason must be addressed with research into available CAD / CAM tools. This can be a frustrating, but potentially profitable undertaking. The second simply is invalid. If undertaken correctly, an appropriate CAD / CAM installation can (and often will) pay for itself on a single project. There is no rationale for the third. Because an operation is successful, there is no reason not to make it more successful.

What can CAD / CAM do? The major effects are summarized in six categories, explored in this paper by describing the technology's application in both a boatbuilding and small shipyard environment. If appropriately implemented CAD / CAM:

1. furthers design optimization,
2. lowers production costs,
3. reduces design / build cycle time,
4. improves control of production,
5. reduces error and improves quality, and
6. reduces required expertise on shop floor.

A decade has passed since the beginning of the general availability of the microprocessor. The impact of this evolving and accelerating technology on shipbuilding has been to allow numerical methods of all kinds to be applied to ever smaller scale activities cost-effectively.

This paper describes in detail the successful integration of the commercial realities of the small shipyard in the 1970's and 80's with numerical methods applied to the design, drafting and structural fabrication processes in small shipyards using microcomputers. The construction environments described range from an owner-managed boatyard, through a marketing driven start-up manufacturing company to a unionized, well-established small shipyard. Production histories of each are examined and normalized parameters developed to assist in applying the lessons learned. Some baseline data from one of the authors' early pre-automation boatbuilding experience is outlined followed by an in-depth examination of the two CAD / CAM installations. Every effort is made to present the data in such a fashion so as to make them applicable across the broadest sector of the marine production capability in North America, that is, the small shipyard.

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[3] Numbers in brackets designate References at end of paper.

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The tools

Computer-aided design

Computer-aided design includes software to design a hull, deck and superstructure, and perform various analyses on those models (such as hydrostatics and speed/power prediction). Design in this context means determination of envelope geometry using as input all known requirements with respect to speed, stability, seakeeping, functionality, economy of manufacture and operation, etc. Figure 1 shows the software used in this installation, FAST YACHT/FAST SHIP from Design Systems & Services, Inc.

For CAD/CAM to be most productive, the design process must start with an adequate description of the object being constructed. This description is usually rudimentary in the early stages of design, and through a gradual process of refinement and reevaluation, evolves into a complete detailed geometrical model. A geometry tool that can provide the designer with the descriptive model he needs at each step of the process and, critically, one that will allow the designer to move smoothly from stage to stage along the design spiral is essential [3].

The early phases of design are necessarily repeated many times as the design spiral progresses. With an effective geometry tool, the designer finds himself willing to explore many more possibilities than before, because the geometry of the object is easily redefined. Since the same tool is used throughout the design process, initial approximations are transformed smoothly into the refined final model. This will help eliminate "surprises" in the later stages of design arising from coarse models having been used in early analysis. It has been said that

> ...the general use of computers, are having a significant effect on the type and scope of calculation carried out, particularly in the early design stages. Whereas, previously, approximate relationships might have been used, full calculations can now be carried out, e.g. for hydrostatic and stability data. At the same time, more design variations can be considered up to a later stage in the design process. In the later stages, a more complete study is made possible by the use of computers as more advanced and complex theories can be applied, e.g. in strength calculations. [2]

A good geometry tool must be versatile, capable of providing data pertinent to the current stage of the design, and at the same time provide continuity as the design process progresses. It must be easily driven by the designer to allow him to effectively model his ideas with a minimum of effort, as well as provide accurate data in a form that enhances effective analysis. Finally, it must provide a geometric description adequate for the construction of the vessel.

The FAST YACHT/FAST SHIP geometry tool—The FAST YACHT/FAST SHIP program currently used at Georgetown Shipyard, Inc. and previously used at Crockett McConnell Inc. is a design tool that combines geometry definition and basic hydrostatic analysis. The geometry (or hull) is defined as a B-spline surface that is controlled by a number of vertices. The surface is manipulated by moving and controlling these vertices, and the surface is continually recalculated and redrawn (usually in one to five seconds) as each vertex is moved. The designer starts with a two-dimensional flat sheet, and molds a hull out of that sheet, into three-dimensions. While the geometry is being defined, the designer may ask to see the hydrostatic properties of the object. These properties include dimensional, area, and volumetric properties, such as length, displacement, and wetted surface.

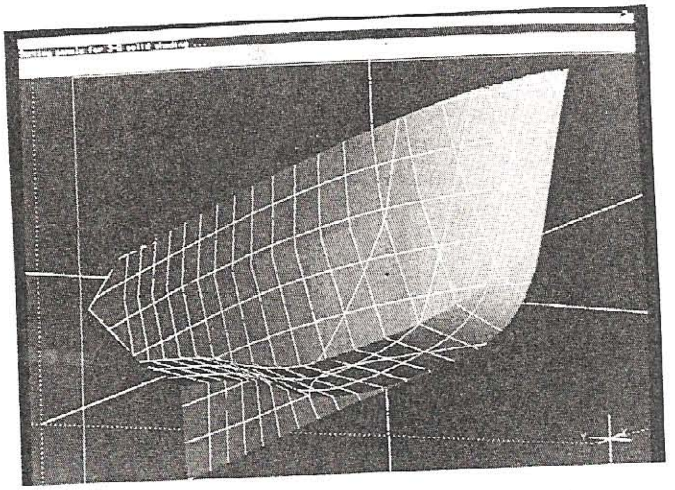

Fig. 1 FAST YACHT/FAST SHIP design screen photo

The hull (or surface) can be displayed in any orientation, and can be represented by B-spline parametric curves, planar cuts (stations, waterlines, buttocks, diagonals, etc.), or as a solid, shaded object. Once the geometry has been defined, a lines drawing and offset file may be created. The offset file may further be used to create files compatible with various CAD/CAM and analysis programs.

As stated previously, the hull is designed by manipulating a three-dimensional net of B-spline vertices. This net surrounds the hull, and along with certain boundary conditions, completely defines the surface everywhere on the hull. As a vertex on the net is moved, the affected portion of the hull is recalculated and redisplayed.

The net is displayed as a mesh of vertices, connected by straight lines. It may be viewed by itself, in any combination of heel, pitch, yaw, and magnification (see Fig. 2*a*). A parallel projection can be used, or a true perspective can be generated of any combination of the net, parametric surface, planar cuts, or solid shading [see Figs. 1 and 2(*b*)].

Since most design is evolutionary, new hull designs typically begin with a previous design as a starting point. The previous design can be scaled globally in any of the three major axes, and then local editing can begin, if necessary. Because of this capability to use previous designs, huge time savings can be reaped with computer-aided hull design.

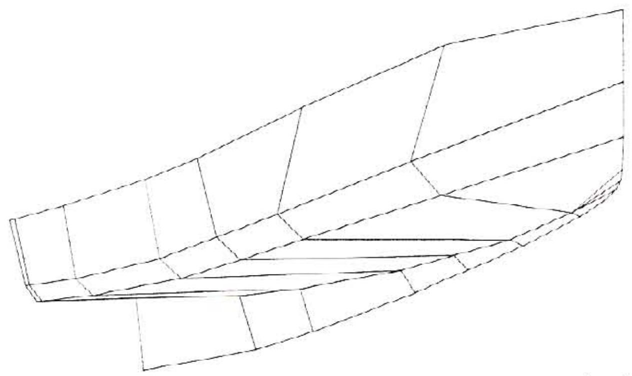

Fig. 2(*a*) FAST YACHT/FAST SHIP F45 B-spline control net

To assist the operator in reproducing an existing design, or matching the character of an existing design, the program can display a digitized offset file during the editing process. This digitized offset file can contain stations, waterlines, buttocks, and three-dimensional curves that are input by the operator from an existing lines drawing.

Developable hulls—One particularly important application of FAST YACHT / FAST SHIP is the design and expansion of developable hulls. Since a developable surface has curvature in only one direction, it can be produced with sheet materials such as plywood, steel, or aluminum without elastic deformation of the shell material at a great savings over forming the same materials.

Creating a developable hull with FAST YACHT / FAST SHIP is truly a design process. The operator first designs the hull without particular regard to developability. As a second step, the hull (or just the desired portion) is made developable by an incremental process of making adjoining net patches planar. This yields a hull surface with at least practical developability, if not absolute developability. When this process is finished, the hull can be further modified while retaining the developability, and the designer may depart from developability in those areas of the hull where it is necessary to achieve the desired shape. When a hull is developable, the parametric curves represent the generators, giving the operator who is experienced with developable surfaces further insight into his design. This design process can be more productive than other methods sometimes used, which allow the operator to define a keel, chine, and sheer, and then try to find developable surfaces that will "fit" those curves.

On-line analysis—While the operator is designing the surface, he may request the program to display the upright hydrostatics. The flotation plane for these hydrostatics is defined by $Z = 0$ in the coordinate system. The operator may change the flotation plane by moving the hull up or down in the coordinate system, or by trimming or heeling the hull. Additionally, the designer may input a desired displacement, longitudinal center of gravity (LCG), transverse center of gravity (TCG), and added or moved weights, and the program will put the hull into equilibrium. The hull will be shown graphically in its new orientation, and the new displacement and resulting trim and heel will be displayed. Portions of a hull—or, if the hull is made up of multiple surfaces, entire surfaces—may be flooded with a specified permeability, and the program will put the hull into equilibrium (if one exists), and will display the results graphically and in a tabular fashion.

A sectional area curve may be calculated and displayed

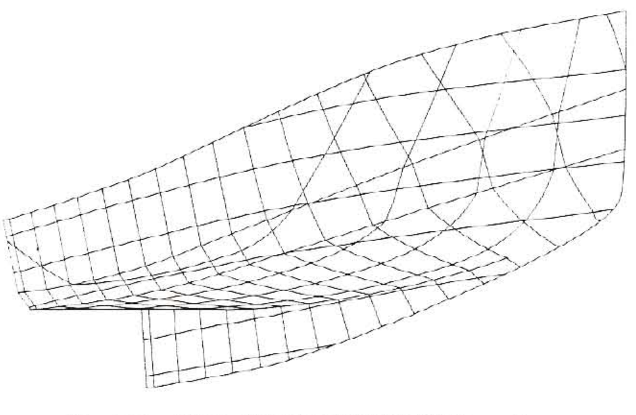

Fig. 2(*b*) FAST YACHT / FAST SHIP F45 sections

superimposed on the hull while in the editing process. As the hull is modified, the sectional area curve is automatically updated and redisplayed. Also, a table may be displayed showing, for each station, the X-coordinate, the girth, and the area.

If the hull type is appropriate, the designer may request an estimate of either planing or semiplaning hull effective horsepower (ehp), based on industry-standard calculation methods. These calculations are based on the integrated properties of the hull and a few inputs from the designer, allowing the designer to optimize his design for ehp as he is designing the shape.

Specific point measurements may be made of points on the net, the surface, or digitized points simply by pointing to them while in the Measure function. The coordinates can be displayed in any of the four coordinate systems available; absolute cartesian, relative cartesian, absolute polar, and relative polar.

Off-line analysis—In addition to on-line analysis, the hull geometry may be used as input to a number of different analysis programs, including complete hydrostatics (curves of form, Bonjean curves, damaged stability, floodable lengths, etc.), planing and semi-planing hull ehp estimation, computational fluid dynamics resistance calculations, and finite element structural analysis.

Computer-aided drafting

Detail design and part definition—Once the surface geometry of the hull, deck or superstructure has been completed, that geometry is passed on to a computer-aided drafting system to be used for detail design and part definition. This geometry transfer can take many forms, ranging from importing the B-spline surface definition itself to passing a multitude of sectional cuts through the surface, either in 2-D or 3-D. It should be noted that at this point, regardless of productivity increases later on, the CAD package has a huge advantage over manual methods because of this data transfer. Imagine working on the drawing table and having at your fingertips overlays of any frame, waterline, or buttock to exactly define the hull surface in the area that you are working. This is exactly what the CAD operator has: precise hull geometry, full scale anywhere he needs it.

In many ways, CAD (D is for drafting) is simply an automation of the drafting board. A good software package will mimic the way a draftsman works, with construction lines, varying line types, different unit and coordinate systems, and different scales available. The drafting task is made easier with the capability to quickly erase, move, copy, and scale individual lines and arcs or entire parts and assemblies. Automatic dimensioning and parametrics reduce the possibility of error. Part and symbol libraries, which can be stored on disk, eliminate tedious copying of repetitive items, and allow the draftsman to include detail on drawings that before might just have been schematic in nature. (There is a danger, however, of using this capability to overdetail what should be a simple, pictorial drawing. This can eat up valuable computer and user time, and confuse the original intention of the drawing.)

There are two major types of output from the CAD system. The first is the plotted hard copy, the standard drawing that can be used on the shop floor or in the design office. Figure 3 shows a drawing generated in Hewlett-Packard's ME-10 drafting software. The second, and more important in terms of automation of manufacturing, is a data file that is the input to the CAM software. The part definition developed by the draftsman in the CAD pack-

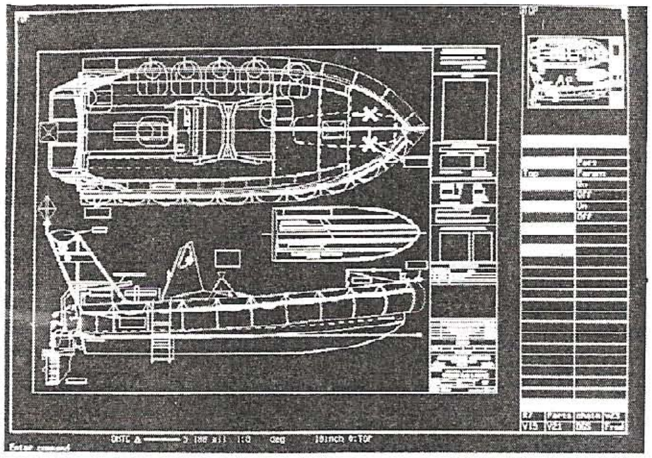

Fig. 3 ME-10 drawing screen photo

age is the same definition that is used by the numerical control (NC) machine.

Computer-aided manufacturing software

The role of CAM software is to take the part definition from the CAD software and create instructions for the NC hardware to actually produce the part. This process can range from relatively straightforward in the case of NC plate burning to remarkably complex with 5-axis milling. Nesting for plate burning may be done in the CAD or the CAM software. The drawing file from the CAD program is stripped of the nongeometry items (text, dimensions, etc.) and a sequence of machine moves (strokes) is created by ordering the geometry around the perimeter of the part (chaining). Lead-in / lead-out paths and connections between parts are determined to create the burn sequence through the plate. Figure 4 shows a drawing created in Data Automation, Inc.'s DGS-2000 software. This global sheet geometry is then processed into machine control language (NC Code), including torch control instructions and parameters such as cutting speed and kerf offset.

Computer-aided manufacturing hardware

CAM hardware can take many forms, as previously noted. Among the most basic, and the one on which this paper will concentrate, is the 2-D burning table for cutting flat plate. The cutting can be done by oxy-fuel, plasma-arc, water-jet and for most of this discussion, 2-D router for cutting wood. Cutting rates for this plasma-arc installation vary from 203 cm (80 in.) per minute for 1-cm ($\frac{3}{8}$ in.) steel to 457 cm (180 in.) per minute for 0.5-cm ($\frac{3}{16}$ in.) aluminum, with a maximum addressable area of 305 by 610 cm (120 by 240 in.).

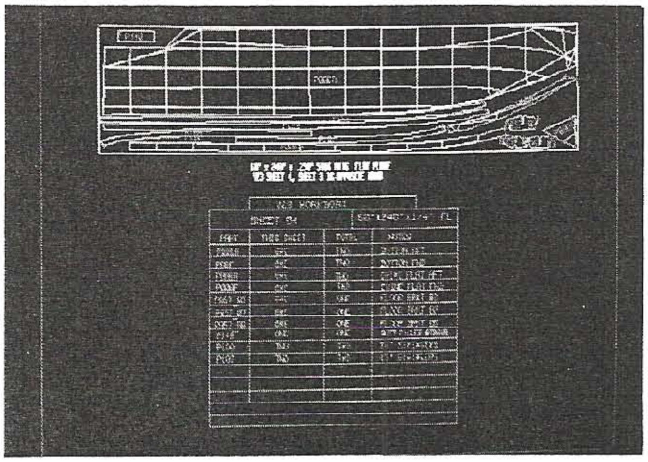

Fig. 4 DGS-2000 drawing screen photo

CAD / CAM implementation

In a unit-oriented industry, advancements in technology and improvements in capability can usually be implemented only at discrete intervals. This requires analysis and planning. Performance must be analyzed using all available data. Accurate records of man-hours by task are required if appropriate implementation decisions are to be made. This is important when many small shipyards may be surviving on estimates and rules of thumb. The experience of management is important in guiding this process but nothing will replace hard data. The possible applications of the next round of technological advance can then be established and their impact, hence likelihood for cost effectiveness, estimated. The planned schedule for implementation has and continues to be an area of concern and potential error. The microcomputer software industry has an earned reputation for broken promises, bugs and "vaporware." A need exists for realism when estimating the likelihood of successful implementation in a specific timeframe. With production schedules, start-up and completion dates and late delivery penalties as part of the equation, reliable running applications that can be brought on line with a minimum of customization and fine tuning are simply a requirement. For this reason a conscious choice should be made to install the simplest solution that will achieve the objective. No attempt should be made to find or make the "once and for all" installation. Because the organizations and implementations discussed here were small and flexible, this was possible, reasonably easy to do and, most important, allowed the "bootstrap" principle to be applied.

McConnell Marine Limited

The entry of the microprocessor into the small shipyard began with the introduction of programmable calculators. If used only to convert inches to millimeters, no one could doubt their cost effectiveness. By leveraging human skills, the microprocessor has brought practical numeric solutions to previously unwieldy problems. One of the earliest expandable such devices was the Hewlett-Packard 41C. The 41C put number-crunching, mass storage and a high-level command language in the hands of the individual. Application specific software was available as early as 1978 in fields such as land surveying with coordinate determination requirements related to shipbuilding. These early machines could print, had nonvolatile memory, branching and looping constructs in a ROM (Read Only Memory) based language and limited alphabetic capabilities.

In 1979, having first used a contract fairing service, and armed with a promising history of man-hours saved in production, McConnell Marine began using a suite of statistics programs available in ROM for the 41C, along with some 2-D geometry solving code written in-house in the 41's internal language, to fair and construct, extremely cost-effectively, numerous smaller steel and aluminum vessels, both pleasure and commercial (see Fig. 5). Al-

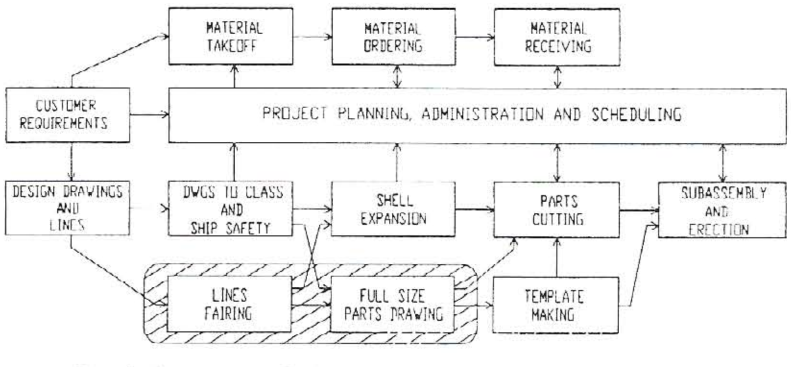

Fig. 5 CAD/CAM block diagram: McConnell Marine Ltd.

though several early personal microcomputers were available at this time, (Commodore PET, Tandy TRS 80), software was rudimentary. The functions required for coordinate determination were available fully debugged in 9-digit accuracy with a few keystrokes on the 41C. Even at this early stage the option of jobbing out the fairing/lofting portion of the construction sequence as opposed to tackling the matter in house was a question to be considered. Bringing this capability into the organization rather than setting up a situation of dependency on a subcontractor was the determining factor in this capital investment decision. The sequence of applying a recently learned lesson through searching for proven software to automate a specific task was an early example of what was to become an on-going task.

After a painful initial period of learning and development, the fairing and construction offset calculations were consistently completed in less time than had previously been spent painting the loft floor, with practically no material cost. The area previously occupied by the loft was regained leaving increased manufacturing space. *This established very early that a planned implementation of existing technology of appropriate scale could be "cost-effective" and indeed resulted in benefits on several fronts.*

As stated, accurate recordkeeping of man-hours by task is essential for making appropriate implementation decisions. These data for McConnell Marine are quantified in Fig. 6 for the steel and aluminum vessels built during this period. Production man-hours are represented graphically by task averaged for 12 vessels, hull numbers 18 through 28, 33 and 35. They establish some "benchmark ratios" of the distribution of man-hours across tasks summarized as follows:

- Patterns: All traditional lofting, fairing, shell expansion, lifting of shapes from the loft floor, template making and jig construction.
- Framing: Fabrication and installation of all Frames, Girders, Stiffeners, and Centerline Structure.
- Shell: Hull and superstructure plating, deck and tank-tops, major and minor bulkheads.
- Welding: All welding, tacking, pipewelding, assembly of jigging and blocking. Welding was tracked historically by task but has been summed here for ease of reference.

For instance, in a procedure such as the subassembly of a bulkhead as a panel and its subsequent erection—the definition of the perimeter geometry of the panel, the marking or programming for the cutting out of the plate, the layout of stiffener location and scribing of reference lines would be charged to Patterns; the cutting, trimming, edge preparation and incorporation into the main assembly would go against Shell; while the cutting, trimming

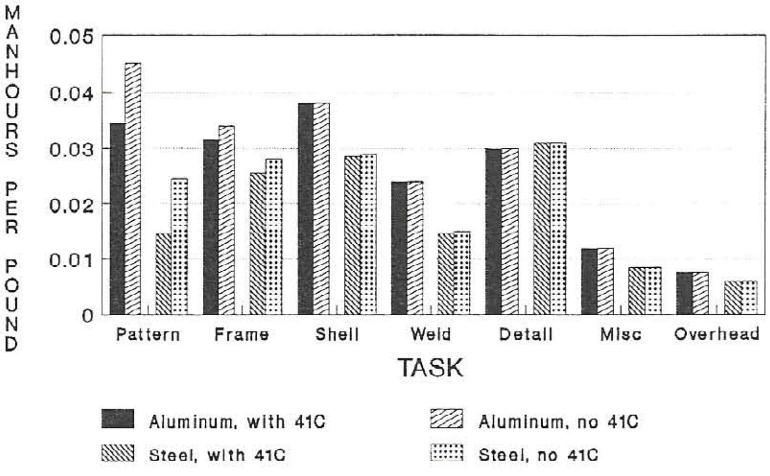

Fig. 6 Man-hours/lb by task with and without HP 41C: MML hulls 18–28, 33 and 35

and installation of all frames and stiffening would be charged to Framing; All tacking and welding for jigging, alignment, assembly and installation would be charged to Welding.

Tracking of man-hours by task allowed quantification of specific gains and earlier identification of bottlenecks than a breakdown into trades (that is, fitter, welder, pipefitter, etc.).

Some leading parameters for these vessels are provided in Table 1. Only those parameters directly concerned with metalworking are included. Normalized production parameters are shown for the purposes of comparison with readily available industry data.

Crockett McConnell Inc.

The application of labor-saving technology was continued through its development in a small (35–50 employee) product-oriented, batch-build Canadian fabricating firm, who chose in 1983 to vigorously pursue a program of developing and implementing microcomputer-based small shipbuilding tools, utilizing emerging microcomputer technology to its utmost. The evolution of this system will be followed in some detail by describing its application and development in a series of design and product development projects. The effects of the application of smarter programs and faster machines will be quantified as part of that sequence.

Over a period of six years, every effort was made to update system hardware and software to the then current leading edge, taking each new advance as it became commercially available and applying it both in design and in manufacturing.

The often-repeated argument against investing now in microcomputer technology, briefly stated here as "It will be half that price next year," was answered with, "There are ways to save money with it today. Buy it now, and use the money saved to buy the improved machine next year." *We couldn't rationalize waiting until next year to save money.*

The early systems were slow, offered poor resolution, documentation and support (more true of software than hardware). They were often less than bug-free, and vendors came and went with alarming regularity. By focusing on what could be immediately applied at and by the shop floor, and carefully documenting where man-hours went, time, and often money, were saved. The importance of documentation was emphasized often when we discovered savings where it was not expected. Hardware and software rapidly got better. Incredible increases in power / cost ratios continued to multiply the effectiveness of these machines and hence their return on original investment.

During this early period, programmers, mathematicians, engineers, designers and others embarked on software development programs to capitalize on emerging microprocessor power. As ship design and to a much lesser degree shipbuilding applications progressed, savings realized from earlier implementations were reapplied, leveraging original capital many times over. Investment took place in office automation as well, with less success in achieving cost effectiveness. It was found that software sold at that time to automate manufacturing management, particularly production and materials management products, could not be cost justified in this scale of one-off and short-run manufacturing.

The key factor in all acquisition decisions was, "Is this the most effective way this capital can be invested to provide cost saving to the company?" Investments in CAD / CAM totalled 37 percent of capital invested for productivity and capability enhancement. Insofar as they were measurable, CAD and CAM were responsible for 80 percent of cost saving and over 90 percent of productivity improvement. In fact CAM undeniably subsidized other capital acquisitions. The gains realized from the replacement of manual methods with numerical methods linked to automated burning in place of manual cutting provided the majority of productivity improvement and cost saving.

In retrospect, the development of a simple, precise and reliable system for retaining hull geometry throughout construction was a critical first step. Smaller yards using manual lofting methods or a contract lofting service retain faired offsets in tabulated form. Access to precise global geometry is lost when the scrive boards are picked up or painted over in the preparation for the next project. An immediate and valuable gain is realized when this geometry is committed to a digital geometric database. This gain is greatest if that database forms the initial geometry definition for the project.

There was a continuous examination of possible new

Table 1 McConnell Marine Ltd. leading ratios

Year	Hull No.	Material	Actual Man-hours	Estimated Manual Man-hours	Savings	Mh/Ton
1980	18	steel	1265	1365	7%	234
1980	19	steel	793	891	11%	258
1980	20	steel	1760	1879	6%	271
1981	21	aluminum	392	456	14%	360
1981	22	aluminum	386	423	9%	308
1981	23	aluminum	386	423	9%	308
1981	24	aluminum	386	423	9%	308
1981	25	aluminum	1120	1218	8%	430
1981	26	aluminum	1064	1197	11%	308
1982	27	steel	825	904	9%	367
1982	28	steel	755	809	7%	274
1982	33	aluminum	468	512	9%	373
1982	35	aluminum	355	423	16%	283
		Total steel:	5398	5848	$ 6091	270
		Total aluminum:	4557	5075	$16 438	340
		Total:			$22 530	

Savings as a % of total sales: 6.7%
Capital CAD investment as a % of total sales: 0.35%

fields of application. With first order gains realized through the installation of a "geometry engine" to achieve additional savings, the diminishing returns available would require more powerful computing machinery. However, as power-to-cost ratios increased by an order of magnitude every two years, further "step-like" advancements were made. Slackening of this must eventually set in, although there is little evidence that this is imminent.

In late 1983, there was a need on Canada's Atlantic Coast for a variety of marine safety products by offshore industries exploring off Nova Scotia and Newfoundland. Crockett McConnell Inc. (CMC), a commercial small-craft manufacturing firm committed to market-driven and product-oriented sales, was formed to address these and other markets. Emphasis was placed on escaping the passive syndrome afflicting many small shipyards. Rather than advertise capabilities and bid with competing firms for available work, niches were sought out where specialty requirements afforded opportunities.

The nature of the work was batch-building of specialized small craft. Immediate initiation of production was required if this existing market was to be addressed. The Coast Guard certification required to enter this market and the prospect of selling to major offshore supply companies prompted CMC to seek a licensing agreement with an established safety equipment manufacturer, Watercraft Inc. of the U.K. Production of the respected *Stills RI22* began immediately, resulting in 12 units being produced in the initial nine months of production. These high-specification, welded aluminum, diesel waterjet-powered "RIB's" were produced using proven manual batch-build techniques, including the utilization of routing templates for production of sheet and plate parts, purpose-built assembly jigs, welding positioners, and dedicated production-line like facilities.

During this first period of batch production an opportunity was seen for improved throughput and flexibility using CAD / CAM. Figure 7 shows the learning curve for the RI22 series.

At the prompting of a venture capital partner, a decision was made to investigate the likely benefits of introducing computer-aided manufacturing technology. The development of a CAD / CAM system effectively addressing the requirements of a small manufacturer (shipbuilder) involved in applying product development techniques to address niche markets was seen as a potentially rewarding application of research. Investigation was initiated on several fronts simultaneously.

Contact was established with the Nova Scotia CAD / CAM Center, opened in 1982 at the Technical University of Nova Scotia. Offering access to a state-of-the-art mainframe integrated CAD / CAM system at the time (Control Data CD2000), consultants from the CAD center demonstrated that mainframe systems had the functionality to address the design development requirements of the offshore and marine industries as we perceived them at that time. An interactive graphics terminal and a modem were installed in the Bridgewater, Nova Scotia plant of CMC on an experimental basis.

A series of visits was made to trade shows and other CAD / CAM centers in Ontario and New Brunswick. The capabilities and cost of every scale of system were investigated.

Shipyards were visited and shipyard managers questioned about their experiences with mainframe systems. Experience and opinions varied. This was a period of contraction for many yards in Eastern Canada and maintaining the system was seen as costly but unavoidable. Trades the system had replaced were no longer available. Monthly or yearly licensing fees were hundreds of thousands if not millions of dollars. Training was expensive and personnel disappeared; immediately there was a downturn.

Vendors were questioned regarding the applicability of their offerings, hardware and software, to our requirements. Those personnel who knew the basics of their product had no idea how to apply it to shipbuilding, whether it was appropriate or even possible. On the issue of CAM most suggested a consultant. They expected to be trusted and asked that we lock ourselves into their system, implying all problems would be solved.

What we knew were exaggerations of the benefits of computer-aided drafting were commonplace. With some growing experience from our time-shared remote terminal, and frustration with the extended learning curve, we were justifiably concerned that the productivity of the marine draftsman, practiced as he is in the real-time visualization of complex 3-D geometry, would degrade waiting for his terminal to redraw, and that simple tasks could blossom into projects in themselves.

Considerable time was expended investigating the ap-

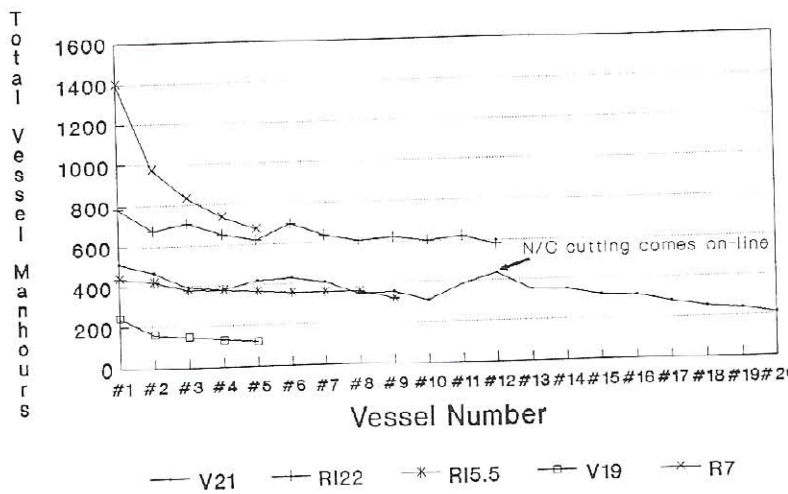

Fig. 7 Construction learning curve: RI22, V21, RI5.5, V19, R7

propriate cutting technology, and its application to the various materials involved. Among issues considered were: working tolerances, repeatability, mass storage capabilities, vendor hardware and software support, reliability, industry standards, environmental concerns, and other topics discovered as we went.

Analysis of man-hours expended at various tasks in batch production was carried out to determine whether the implementation of such a technology could or would pay for itself. We were confident of the validity of our own data—not always so of that provided by system vendors. We became convinced that without a direct link to production resulting in savings in production man-hours, a system would not be cost-justifiable.

Consultants associated with the CAD / CAM centers, although enthusiastic about the possible micro-based opportunities, were inexperienced in small systems CAD themselves. Sure of the soft benefits such as improved quality, manufacturing flexibility and shop layout, they could help little with direct cost justification or in planning a micro-based implementation.

Almost nothing in the way of precedent, background data, literature and even hardware or software was available for demonstration. Individuals with practical experience were virtually nonexistent.

The first hands-on investigation began in early 1984. It was decided to use the terminal linked to the CDC mainframe in Halifax to develop a new aluminum extrusion for a small craft design then under development. The stages in production had been identified. The extrusion was to speed assembly at a particular stage identified as a bottleneck. The development of the extrusion proved to be the bottleneck. The response associated with a 1200-baud serial line was a serious problem. The extended functionality of the software was available only after a lengthy training and learning period (also at 1200-baud). These and other problems, such as the lack of access to hard copy and the cost of time-sharing, were all factors in the decision to continue to investigate CAD systems but to concentrate on the development and writing of a specification that would describe an ideal small shipyard micro-based CAD / CAM system.

The factors in place to make a likely environment for a successful CAD / CAM installation were determined to be:

1. Batch Building—Short to moderate runs, (5–15 vessels), a high labor content, often with a requirement for certification to a national or international standard. Traditional methods suffer from high start-up, tooling storage and maintenance costs, long production development cycle times and repeatability problems. CAD / CAM offers the prospect of addressing all these factors.

2. Requirement for Precision and Quality Assurance—Emphasis on high-speed small craft often identifies aluminum as the material of choice. Strict requirements on assembly tolerances and welding frequently necessitate rework on manually produced parts. Product and procedure certification often requires dimension control of individual assemblies as well as finished product. A need exists for predictability.

3. Frequent Minor Variations from Standard Designs—Within a batch, even a single customer can specify minor variations, more easily achieved with a computer-based manufacturing system.

4. Lack of Trained Labor Pool—As a start-up company, CMC needed access to a skilled labor pool to grow. The multiplying effect of automation is attractive. Training is required. Why not look for tools to optimize that effort? Parts produced by an automated system require less skilled help in assembly. Better fitup improves welder productivity. Available skilled help can then be employed overseeing production and not be tied to time-consuming, error-prone tasks such as lofting, shell expansion, projection, development, and pattern and template making.

5. Simple NC Machine Requirements—The possibility of automating a significant portion of production man-hours with one NC machine exists. Study shows that 12 to 20 percent of production man-hours go into part geometry definition, part layout, cutting and marking. Some payback can be expected in assembly from improved accuracy and repeatability.

The majority of interactive graphics systems in 1984 were minicomputer based. Personal graphics workstations were years in the future. Their predecessors were only just becoming available. One such machine early in its development was the Hewlett-Packard 9816, later to develop into the 200 series and eventually the 300 series of technical workstations (the HP 9000 series). By late 1984, some CAD applications were emerging for this environment, utilizing the extended Hewlett-Packard Rocky Mountain BASIC (RMB) and Hewlett-Packard Pascal, both well supported by Hewlett-Packard.

One such application was Design Systems and Services' FAST YACHT / FAST SHIP. The cost, support, expandability, reliability and communication capabilities of this hardware platform and the emergence of software such as FAST YACHT / FAST SHIP looked very promising. The software developers were themselves naval architects and yacht designers. The interface was conceived and built around interactive surface modeling. Developed by designers for designers, the learning process was smoother and less painful than anything we had seen previously. There appeared to be real potential for cost-effectiveness in hull design and lofting. We would still have to achieve the link to production.

The investigation into cutting processes had indicated plasma arc cutting of aluminum as the technology of choice. Its suitability for high-speed cutting of mild and stainless steel as well makes it flexible enough for the great majority of shipyard cutting tasks. Other possibilities were rejected as too slow or too expensive. A narrow choice of vendors indicated the wisdom of choosing an industry standard machine, compatible with the installed base in the marine industry. In this case a Linde CM250 with UCNC7 control, maximum onboard memory, and a DNC (Direct Numerical Control) port was chosen. Downloading and uploading of NC files through this communications port eliminated any requirement for paper tape and utilized mass storage in the CAM computer as on-line storage for the cutting machine. One hedge that was required when the machine was purchased was the provision for tracing and cutting from paper patterns. This proven optical system, still in daily use in many shipyards, was specified as a backup if the numerical system we were developing proved to be impractical. It has never been needed. Because code produced by the optical tracer is identical to NC code produced by the machine control, this capability can be used to capture an existing physical pattern inventory for computer nesting and NC cutting.

Early (pre-CAD) production of NC code consisted of a process similar to computer programming where machine language constructs were typed into a text editor and then submitted to the machine control as a program, with the attendant de-bugging requirements of any other type of programming.

Early micro-based 2-D CAD systems were generally automated NC programming systems capable of generating NC code from symbolic input (post-processing) with CAD-like graphics creation and editing functions added later. One such system was Data Automation's DGS 2000. Developed in the Hewlett-Packard RMB environment, this integrated 2D drafting/NC package was chosen to form the link from the HP200 to the shop floor by means of RS232 serial communications. A postprocessor capable of generating NC code for the Linde UCNC7 control was developed and added to the software.

Installation of computer, software and NC burning machine began in September 1984. In mid-November we were ready to bring the burning machine on-line. Initial experience drafting with the CAD system did prove what we had anticipated. Generation of detail shop drawings often took two to three times as long as manual drafting. Operator inexperience, slow screen redraw and disk access, poor graphics editing functionality, and poor screen resolution were all contributing factors. It was important that the characteristics of projects with paybacks be identified. Whenever geometry was to be reused (stock components and standard details), or if absolute precision (metal part geometry) was a criterion, the payback was generally assured.

A library of standard construction components and tooling parts was built up, available to be plotted at any scale as required. Simple components with geometry independent of global ship geometry (doublers, brackets, etc.) were drawn, nested, post-processed and down-loaded in the initial stages of implementation.

V21 initial production—The first full use of the system was in automating a design in current production. In anticipation of utilizing NC cutting, an existing design had been modified to utilize the anticipated increased cutting speed. It was assumed that the NC machine could be used to make parts with more complex geometry than could be effectively produced manually. They would, when accurately produced by NC code, make assembly quicker and finished product more finished in appearance. With some delays in installing and de-bugging the system we had reached Hull No. 12 when the first NC cut parts reached production. This made early vessels very costly in man-hours. The learning curve of that series, presented in Fig. 7, shows how details that are inappropriate for existing technology can impact negatively on production. Throughput rates are significantly lower in early production but rise once NC cutting begins. Smooth operation of the cutting process took time to bring on stream. We underestimated the additional demands on material handling. This took several months to straighten out. This first project was input manually by measuring the pattern for each part, reproducing the geometry in the computer and drawing its contour. Surface modeling is unlikely to produce a set of lines identical to those resulting from manual lofting. Rather than risk producing parts that would not fit on existing tooling, the full size "database" was utilized.

In capturing an existing design, many steps in the design/build process were tested. Conversion by the CAM program of graphic data, in the form of nested plates, into ASCII code used as program data by the burning machine automated the NC programming task. Storage of code on disk and downloading using serial communications in place of paper tape simplified data storage and shortened NC program development time. Repeatable high-speed cutting of precision parts validated previous estimates of the magnitude of production man-hours saving.

Surface modeling allowing interactive sculpting of hull lines, on-line hydrostatics, and commands for constraining hulls to general sets of developable surfaces; accurate and fair lines plans with tabulated offset output were similarly useful tools in the design process.

An immediate requirement was a digital data link from surface modeling to drafting and hence to NC code, thus closing the loop between design and production. This would require cooperation between software vendors to establish a common data and media format, as well as a comprehension on the part of software developers of the needs of end users concerning the functionality of data input and output procedures.

A batch system was specified whereby, at the time of lines plotting, a set of files could be optionally created on disk that would contain 3-D coordinates of points representing the geometry of the slices through the surface shown as section, buttock, and waterline curves on the lines plan. Each file contained a set of points, planar in the case of section slices, 3-D curves in the case of surface edges, for each curve specified. The number of points calculated, and hence the resolution of the surface, was made to be user-definable at run time. These files were written in a format known to a function installed in the drafting program. By calling the file into the drafting program using this function, an outline of the hull, being the exact geometry of the planar slice through the surface at that location, was displayed on the screen as a series of 3-D points mapped onto a user-defined plane. The geometry creation and editing tools provided by the drafting package could then be used to define and draw whatever detail structure—frames, girders, tanktops, brackets etc.—existed at the chosen section, using the hull outline as a template and boundry.

Because the mathematics of B-spline surfaces generate section slices that are by their nature fair, the set of points saved representing each section slice lies on a fair curve. The problem of cutting out parts with truly fair curved edges is thus reduced to developing a method of connecting the points and eventually generating an NC code that retains this fair curve.

The simplest method would have been to specify an arbitrarily large number of points to be generated along the surface intersections. Straight lines could then be drawn and subsequently cut between each point and, with points sufficiently close together, no significant error would occur. This would have created very large files, especially where rates of curvature are great. NC files, consisting of a line of ASCII code for each of these points, would have been unmanageably large. Constraints such as the size of DRAM (Dynamic Random Access Memory) available on the cutting machine would have severely limited the number and size of nested sheet files that could have been downloaded at any one time.

A method of representing the fair line of these points using a series of successive arcs was an important development. An algorithm was developed and built into the drafting software that cycled through the list of points representing the section, selecting an arc that would pass within a user-definable tolerance of the first and as many subsequent points as possible. When the largest set of points was found that all fell within the tolerance, the arc would be drawn to the last point in the set and the procedure begun again at that point. We found that even a very small tolerance (2 to 4 thousandths of an inch) resulted in reductions in the order of between 5:1 and 20:1 in the volume of data required to define the curve within the cutting tolerances of the burning machine. The procedure automatically inserted a sharp corner where curvature was instantaneous (at a chine corner, for instance). The raw point files were retained (off-line) for archival purposes, and working files resulting from this data reduction were used for the generation of NC code and working drawings. Checks for extremely long radius arcs and very short chord lengths were developed to keep the NC code within the addressing limits of the cutting machine controller.

This has proven to be a very effective method of ensuring the creation of fair edges to curving plate parts when the input data are the product of intersections with B-spline surfaces. This can be attributed to the fair nature of the surface and hence to the data set itself. No fairing of data points is done in or by the drafting software, thus assuring the production of plate parts that will build a vessel exactly as created by the designer in the surface modeler.

Results have been poorer when the same process of data reduction using arcs has been used to reduce data sets generated by non-B-spline surface methods. Lines fairing using interpolation of intermediate 2D and 3D splines from a master set of curves results in sections that appear to oscillate from one side of the actual fair line to the other. Because there is generally no increase in the quantity of data points generated in areas of high rates of curvature (this increase is a natural result of the use of B-spline surfaces), fairness is not consistent. In projects involving "job shop" work with lines faired by other software, we have had to resort to manual placing of individual arcs through selected data points, plotting of the resultant curves large scale, and validating fairness visually. Several iterations of the process may be required, a process both time-consuming and error prone. Cross fairing (buttocks against sections for instance) is generally impractical, resulting in imperfect fitup and necessary rework of parts during assembly.

Although suffering from late implementation of a technology assumed to be in place during the design phase, the initial V21 production run did prove high-speed, accurate and consistent parts cutting to be achievable. An effective interface between hull modeling and detail design and drafting was conceived, specified and put in place. Immediately, the design effort focused on utilizing the vertically integrated system in a full design cycle.

R5.5 design and production—Interest among safety professionals was focused on a downsized rescue boat that would fit on the crowded decks of many Coast Guard Search and Rescue (SAR) cutters. Having obtained confirmed orders through Canadian Shipyards for two 5.5-m boats to be fitted aboard CCG SAR vessels in midlife refit, we initiated a program to put the system to work.

With the RI22 as a baseline, in cooperation with Watercraft, we developed and brought the R5.5 to market. A batch of nine vessels was built for government, offshore, hydrographic and seismic exploration clients. The entire design/build cycle took 14 months. The learning curve was steep with most gains coming in the initial three vessels, as shown in Fig. 7. This effect has proven to be typical. Total hours averaged less than 60 percent of the RI22, bettering our most optimistic estimates.

A mix of computer and manual drafting methods was used. Generally structural, that is, metalworking, drawings utilized CAD, while machinery, electrical and auxiliary systems drawings were produced by hand. Load on the single CAD/CAM workstation from production requirements meant that only drawings requiring the system for NC output could be allotted time. We found the computer slow at generating and manipulating text. System drawings in small vessels, if significantly of an illustrative nature, were more quickly produced by a talented designer/illustrator. Faster, more functional systems have since changed this equation markedly.

Access to precise hull dimension data and any orthagonal section at any scale did make the systems and outfitting design tasks easier. Components were drawn in multiple views as training exercises, making them available as templates in the manual drafting stage. The benefits accruing from the ability to plot these at any scale for use in manual drafting are an example of a significant and unanticipated gain.

This first full-cycle design project produced a more detailed set of drawings rather than a net savings in time. The natural tendency to overuse a new capability requires disciplined handling with the introduction of CAD. The system becomes clogged with data if every detail is reproduced at its every occurrence. The tendency to iterate toward perfection impacts adversely on cost-effectiveness.

As a modern high-performance small craft, the R5.5 was a thoroughly unremarkable shape. A moderately deep-vee (17 deg), developed surface hard chine model, it was ideal as a first full-cycle project. A moderate production run absorbed the cost of introducing new design tools, including a one-time increase in front-end costs due to operator inexperience.

SL31 design and development—In early 1985, as a result of success using CAD/CAM as well as a corporate decision to broaden its product base, CMC, in a venture with Canada's Department of Fisheries and Oceans (DFO), undertook to develop a new generation of high-speed hydrographic survey vessels.

DFO specified a semidisplacement 31-ft (9.5 m) launch with a service speed of 17 knots, 16-hr endurance and the ability to sound effectively at that speed in sea state 4. An interesting design project in itself, the CAD and CAM related aspects of the program are the focus of our attention.

Starting from a tested set of semidisplacement lines, our interest was to optimize the producibility of the required round bilge hull shape. Utilizing an intrinsic mathematical characteristic of FAST YACHT/FAST SHIP's B-spline tensor surface, wherein the generators of a developable surface lie on the net lines generating the surface, a "close to developable" shape was worked up. This was a set of lines requiring an absolute minimum of plate working to achieve the required fitup. The lines were represented using a net whose control lines ran parallel with the anticipated roll lines in the plate. A combination of an experienced plater's and the designer's skills was required.

A developed shape was departed from or used to advantage where appropriate, considering design requirements. Otherwise the shape was kept as fair and "round" as possible to maximize flow attachment with resulting clean sounding characteristics. Shell plate working was effectively minimized (except for shrinking required around the edges of the bilge strakes) and a highly producible design resulted. With the precise control over metalwork production afforded by the CAD system, the finished vessel came out exactly at design weight and performed to specifications with respect to speed, sounding characteristics, endurance, and operating accelerations.

One persistent concern with CAD implementation surfaced during this project. Experienced design and production personnel are valuable assets of any manufacturing firm. The effective application of their talents is critical to the technical and financial health of the organization. Their removal from production for training strains the resources of the organization, placing responsibility for their tasks on others. The investment of time and money has a rate of return dependent on their talents, interests, and abilities. It is important to budget for this as part of overall costing for implementation. Selection of personnel for training is likewise a serious consideration. It is a hard reality that younger, newly graduated engineers and technical personnel will have the most up-to-date theoretical background while the weathered "old hand" will have the experience. Optimizing the productivity of automated tools requires a mix of these skills. Intuitively it makes more sense to teach a talented designer about computers than to take a computer scientist and teach him or her about design and product development. Not all old hands react well. Some feel threatened, which may have a role in blocking their comfort with the technology. Implementing CAD / CAM places design and NC programming at the front end of the manufacturing process. The control this gives management over the process is a major benefit. A situation is created where alternatives to streaming projects through the CAD / CAM system are eliminated as resources are committed to automation. If this is unplanned, a situation can arise where time inevitably lost to the learning process cannot be spared. This is referred to as "There is no way to get there from here." Personnel cannot then be spared from critical production tasks to be trained in new methods, so time savings generated by the results of training can never be achieved. This is an unfortunate and real problem, potentially more than offset by the benefits of leveraging the talents of these valuable people. Some excess capacity must exist or time lost to training will be an unbearable burden.

Rates of learning varied. Some talented persons made very little progress in achieving acceptable productivity rates using the computer. With significant resources committed and successful production of graphic and NC data an absolute requirement, it was necessary at more than one point to cut short an individual's use of the machine and promote use of it by persons demonstrating adequate production rates. These were painful but necessary decisions. The success of the project and the organization demanded it.

Formal training, out of the shipyard environment, for both managers and operators by an outside CAD expert is required if benefits are to approach their potential. This is partially because no shipyard system manager can have the breadth of experience that exposure to other disciplines gives a generalist. We have much to learn about micro-based CAD / CAM in its current state of development from users in other fields. Most development is going on in individual sites through application-specific experimentation (not significantly different from large-scale implementations). Others will have been exposed to situations that have not yet occurred in the shipyard. Having faced different but related sets of problems, their solutions may have relevance in your application.

There is no single solution to the challenge of appropriate human resources development. The situation is perhaps little different in CAD / CAM than it is in other technical fields. The problems are compounded when the capital costs of implementing the technology are justified assuming successful productivity in the near term, when in fact the process of "getting up to speed" requires a period of adjustment and displacement of necessarily productive design and production staff.

F35 design and production—By mid-1985, the first cycle of productivity development was essentially complete. A system existed in which we had gained confidence through two complete design cycles. The products developed were cost-effectively produced and generally accepted in the marine community. A small but versatile group of operators offered a good measure of redundancy. We had minimized our exposure from being at the leading edge of the implementation of the technology. We were ready to take another step.

The local fishing industry is a dominant regional economic force. New vessel construction follows the cyclic nature of the harvesting industry. Fiberglass construction has dominated the inshore fleet, recently fashioning glass-reinforced plastic (GRP) models on successful wooden vessels.

CMC planned, through open meetings with inshore fishermen, to poll opinion and, based on input, to create a new design, respecting traditional appearance and seakindliness and offering the maintenance advantages of welded aluminum.

This undertaking could be competitive with wood and fiberglass construction if production man-hours were absolutely minimized. We were in a new position to achieve this. Considering the resistance to an unproven material in a conservative industry, the decision was made early to design a vessel with as close a resemblance as possible to the existing fleet.

Department of Fishery policy for the inshore fleet uses overall length as the sole parameter for licensing. With a healthy resource fueling newbuilding and North Atlantic weather a major factor affecting consistent harvesting during fall and winter seasons, vessels have naturally gotten beamier and deeper. To produce in metal such a beamy round bilge vessel cost-effectively would be a challenge.

The favored lines resisted attempts to reduce them to anything near a developable surface. Open discussion had indicated there would be resistance to a multi-chine shape. The lines of a modern Cape Island style of hull were modeled and scantlings developed to match the high loads expected during service from the impact of offshore lobsterpots on the topsides (see Fig. 8). A contract was signed with an owner from the Digby region on the North Shore of Nova Scotia, an area subject to the Bay of Fundy tides. Skeg, bottom plate and framing were strengthened in anticipation of the vessel regularly taking the bottom, often

Fig. 8 Crockett McConnell Inc. F35 fishing vessel

in adverse onshore conditions during the area's off-season herring weir fishery.

The result of this ad hoc development was a disappointing project, demonstrating a principle fundamental to successful CAD / CAM implementation: Start with what you know and move slowly, changing only what you can reasonably expect will work, utilizing the unit nature of vessel construction to add the lessons of earlier experiences to successive cycles.

With this design, far too much was tried in one cycle. As a problem project it is perhaps of greater interest than many of the successful ones. It was key in underlining one lesson: CAD must be seen not as a problem-solving technology, but as a productivity improvement technology. That is, CAD can perform well if intelligently and appropriately applied in a planned fashion in a field familiar to the implementors. If conceived of and introduced as a solution to a problem, it will almost certainly compound that problem.

Our success in the survey launch project had not prepared us for this little fishing vessel. Lack of computer tools for accurately determining the position of longitudinal stringers on the surface resulted in a delay in the detail design stage and considerable rework during assembly. Unresolved compound curves in the lines, aggravated by very heavy scantlings, resulted in overruns in plateworking. Unusually large welding distortion, traced to unresolved stresses resulting from this plateworking, led to alignment difficulties with propulsion and steering systems. Schedule overruns in metalwork detailing in the design stage resulted in missed milestones in machinery and systems detailing. This carried over into schedule and cost overruns in outfitting and commissioning. Delivery was targeted to meet the opening day of lobster season. The frustrated owner had to be content with a vessel chartered by the builders for the opening week of the season.

We examined the extent to which the CAD system had exposed us to such fundamental mistakes. Was the problem overconfidence? Misapplied technology? Was the system up to the task? It was no doubt a combination of factors, including lack of required CAD functionality and throughput, inappropriate conclusions drawn from a previous project, and poor project definition. More research would be required before a decision could be made concerning the fit of this market to CMC corporate goals. Fortunately, the performance of the vessel met with the owner's expectations. The vessel was made available for working demonstrations for fisherman at the end of the first season. There was considerable interest. The low maintenance requirements of unpainted aluminum and the advantages of strong lightweight construction were obvious. However, lower costs had to be realized if CMC were to enter the market.

As an experiment, a set of similar, but multi-chine, developed surface lines was modeled and the lines plan displayed aboard for comment. Surprisingly, many thought they were the lines of the vessel they were aboard. When told otherwise, most conceded that such a vessel would not be in any practical sense inferior to the round-bilged shape except possibly aesthetically. Some even volunteered the comment that there could be advantages (the shape is stiffer and drier, but noisier). Most, we concluded, would think about no difference other than cost. If it would make the vessel more economical to build, it was what was wanted. We concluded that a developed surface vessel was required.

Surface unwrapping software development—This led directly to a significant development program in the progress of the CAD / CAM system toward becoming a complete small craft building implementation. In consultation with the software developers, CMC wrote a product specification defining a surface unwrapping and section intersection mapping module that would do to plate expansion what the original geometry file saving scheme had done for transverse and longitudinal structure. This ambitious plan would tap the developable surface generation techniques built into FAST YACHT / FAST SHIP and provide automatic creation of expanded shell plate files. Additional requirements were the development of general tools for defining surface slices to be mapped onto the unwrapped plate. This would allow the marking of mold lines and other planar shell intersections on shell plates by the cutting machine prior to parts cutting. In smaller vessels the shell plates could then be cut in one piece and assembled first, with the framing and other precut structure dropped in afterwards. Having mold lines on which to place appropriately cut structure would reduce construction to assembly in many cases. A new possibility was the utilization of parametric design techniques, reusing existing models by scaling or stretching basic dimensions globally within the surface modeler. Unwrapping the resulting surface would yield an entirely new design with a potentially high carry-over of usable parts from the parent design.

F45 design and development—A lesson resulted concerning ambitious software development projects. As a direct outcome of the introduction of the 35-ft (10.6 m) lobster boat, CMC was approached by a neighboring operating to design and build a 45-ft (13.7 m) herring carrier. Essentially a floating tank, utilized to transport herring from the offshore seiner to a processing plant ashore, this design fully utilized the characteristics of aluminum. Optimizing carrying capacity is the principal concern of the owner, with stability—considering the large potential free surface of the wet cargo—a significant design consideration. Generous fixed ballast could be fitted in the aluminum hull without reducing capacity. The hold, if framed only athwartships, would be a corrosion-resistant food-grade tank, draining fully to an easily maintained sump.

A design / build contract was signed with the assumption that the surface unwrapping capability would come on stream in ample time to be utilized in the construction. In fact, the scheduled development period of two months stretched into a full year. Although the fallback plan did not in the end have to be implemented, this clearly demonstrated how a production plan, dependent on software tools still under development, must account for every eventuality, including reverting to a manual system.

The labor profile for this project showed a dramatic improvement in throughput over previous projects. No other single software tool has equalled its overall cost-effectiveness in reducing production labor requirements, not only directly in plating tasks but globally in the layout and installation of framing, in welding, and in outfitting. Entirely new approaches to small craft construction have become available. It has become possible to compete in sectors previously closed because of high labor content. The overall distribution of man-hours has been significantly altered.

A digression into the disk operating system (DOS) environment—At this point CMC's CAD / CAM system had reached a crossroads. A development project, simmering in the research office, had reached the boiling point. Major construction projects (two America's Cup contenders) operating independently of the CAD system were nearing completion. Through its implementation in pilot projects, the cost-effectiveness and thus the commercial feasibility of CAD / CAM implementation had been established. A decision was made to put in place a system capable of providing a fully computerized design-and-build front end for the organization.

Using data collected from the pilot projects described, we determined the approximate throughput requirements of a commercial-scale implementation. It was evident that additional design workstations would be required if the geometry definition and detail design requirements were to be met totally by the computer system. A study was initiated to determine the state of the micro-based CAD / CAM market to identify potential vendors. The CAD Centre at the Technical University of Nova Scotia was again consulted. An internal survey was undertaken to formally gather input from operators and implementors regarding all aspects of their interaction with the system.

By this time (fall 1986) considerable advancement had been made in PC-based CAD products. With the intent of utilizing, in planned further system development, some of the broad scope of software available for the MS-DOS environment, a decision was made, after an exhaustive study, to install an early 80386-based PC (personal computer) equipped with high-resolution graphics, a fast hard disk and tape backup, running a Canadian-developed drafting and NC product (Accugraph's Multidraw / MultiCut).

This decision was contingent on the successful development and implementation by the PC software vendor of interface utilities to parallel the automated data capture and reduction techniques we had implemented ourselves several years earlier, but this time within the vendor's proprietary environment.

Autocad's DXF drawing data exchange format had achieved the status of a de facto standard. This format was selected for data exchange. Translators were developed for the installed software (FAST YACHT / FAST SHIP and DGS 2000) to permit migration of existing design data and continuing data interchange. This proved to be very successful and has been expanded. Only partially implemented and used on an ad hoc basis for less than a year, the data capture utilities for the DOS workstation never delivered the functionality specified. The implementation fell victim to a common ailment of the DOS software development industry. Products grow old quickly. Developers come and go and acquisitions and mergers leave redundant products in their wake. Graphic workstation prices had begun dropping dramatically. The software we had selected was seen to be nearing the end of its product cycle. We had already experienced several missed delivery dates. With fear of worse to come with potentially orphaned and unsupported software, we felt ourselves fortunate being able to withdraw from the agreement, the vendor having failed to deliver the interface utilities as specified.

The deciding consideration in the choice of a PC had been the plan to install some of the abundant fully developed software available under DOS. This included a project management package as well as a database product we knew could help in managing the proliferation of component and metal parts files generated by the design process (typically in the thousands even for small vessels). This was further indicated by the potential parametric design functions then under development in the surface modeler. The availability of cost-effective functional software for DOS was perceived as being in contrast to the scarcity, cost and sparse functionality of products available for other proprietary systems.

The computer-intensive nature of CAD left no time whatsoever for these other tasks. The cost of the graphics hardware in the PC could not be justified in supporting these other functions. The tradeoffs of somewhat lower performance in the PC environment (over the dedicated graphics workstation) for access to a software base was self-defeating in that the lower performance cut off access to the software due to time constraints. The low cost of 80286 based PC's could have been justified in a support role for the CAD station. When the DOS CAD station was replaced with a Unix workstation, this software eventually migrated to a 386-based PC dedicated to scheduling and project management. The far less costly equipment has performed adequately, accessing expensive CAD peripherals (plotters, laser printers, etc.) through inexpensive serial switching devices. Data are swapped in and out of the CAD environment by disk sharing of ASCII files. The interfacing techniques developed have proven useful and of general utility.

V19 and V21 parametric design—The design project initiated during the period of experimentation in the PC environment involved the utilization of the parametric capabilities promised by the techniques developed for surface unwrapping. This program, still ongoing, will be looked at in detail.

Parametric design is a development of the most useful characteristics of computer-aided design. Simply stated, it is the replacing of specific design parameters with variables to allow the creation of a "family" of designs generated by the systematic assignment of values to the variables. Particulars such as length, beam, draft and displacement must be linked with parameters such as shell thickness and stiffener section modulus. In a vessel of any size or complexity this can quickly become impractical; however, in a relatively narrow range of smaller vessels it has proven to be quite possible and very efficient. The cost-effectiveness of the simple expedient of reusing data cannot be overstated.

CMC had niche markets in the Canadian Arctic for specialized high-speed craft since its inception. The V21 addressed that market for several years. Surface unwrapping brought new capabilities to bear on this specialized product. In late-1986 a market was identified for a more compact version of the V21. A rework of the structure was required if the techniques of parametric design were to be applied. Some tradeoff analysis was done to determine the most advantageous breakpoints. A continuous sliding scale of sizes was determined to be uneconomic. Step increments in available material sizes were enough to determine the most practical sizes. Sheet from coil can be purchased in any practical length, but width is a constraint. The fixed burning machine dimensions appeared to limit choices. An addressable length of 20 ft (6.1 m) on the cutting table made a 19-ft (5.8 m) hull possible with unwrapped topsides just under 240 in. (6.1 m) long. This would be the parent hull.

If nested in 5-ft-wide (1.5 m) sheet, when scaled to 6-ft (1.8 m) wide the resulting expansion in the length required a 24-ft (7.3 m) sheet. A technique was developed for re-registering the material to permit moving it after cutting was partially complete. This was determined to be cost-effective over lengthening the machine table when costs of providing floor space for the addition were considered.

A small craft family varying in capacity by a factor of 2 can be produced by varying the length parameter alone, (stretching of parallel section) in one of two different scales. Parts for the two separate scales of the design, varying by a factor of 6:5, are produced by proportionate scaling of the nested sheets of the parent design in the CAD program and re-postprocessing. A combination framing system, using plate floors notched for bar longitudinals, was used. All curved stiffeners were NC cut from plate. Straight-line stiffeners in the afterbody were extrusions. Judicious choice of stiffener sizes allowed use of wider and thicker sizes in the scaled-up version to fill the enlarged slots. The resulting greater stiffener spacing was accommodated by an increase in shell thickness. It took a physical model to convince skeptics that a developable surface would remain developable and hence accurately unwrappable when scaled along one axis only!

What were considered optimistic budgets for production man-hours were halved. Targets were actually lowered during the short pre-production run. A distribution of man-hours for this project is contained in Fig. 9. For the first time material throughput exceeded 9 lb / man-hour (4 ks / man-hour). For thin metal work, without hard tooling, using only flexible programmable machinery, we considered this a breakthrough. This was achieved with the short learning curve plotted in Fig. 7, in contrast with the initial 20-vessel run of V21's, also shown in Fig. 7. There appears to be an effect whereby once familiarity with the set of parts is gained, high production rates are achieved very quickly.

The scalable design has initiated a building block approach to addressing customer requirements. Work is proceeding on a related approach to superstructure modules. Hull and deck can thus be married with an owner's choice of wheelhouse, scaled if required, rendered as a 3-D shaded model in the surface modeler for visualization purposes. The view is generated from any position, including that of the helmsman and output as color presentation copy. This has proven to be a significant sales tool as well as an effective design development aid.

Georgetown Shipyard Incorporated

In mid-1987 it was decided that the commercialization of the system would be most appropriately achieved through its sale into an environment where it could address the automation of a significant number of man-hours. A close fit was found with Georgetown Shipyard Incorporated (GSI), a provincial Crown corporation, owned and operated by the Province of Prince Edward Island. A small, un-automated shipyard, addressing fishing and government fleet needs with a labor force of approximately 100 hourly paid employees, GSI has 25 years' experience in construction of a wide variety of often specialized vessels, offering a custom service sometimes shunned by the larger mainland yards.

Located on the eastern tip of the island province, GSI has a stable labor force but is unable to tap a significant industrial base. Subcontracted work often has to be placed off the Island. As the major steel fabricator on the Island, GSI has limited industrial fabrication work available. There are limited possibilities for expansion of the labor pool. These factors combined make GSI very likely to benefit from an appropriate implementation of computer-aided manufacturing. In the spring of 1988 the computer systems and the associated manufacturing machinery were relocated from the Bridgewater plant of CMC to Georgetown PEI.

It was decided early not to dedicate all computer resources to bringing a three-ship newbuilding program, already underway for eight months at the shipyard, into the system immediately. An effort would be made to broaden the product base of the yard, undertaking the design and construction of smaller vessels as well as seeking to establish a specialized metal parts cutting service to nonautomated facilities throughout Maritime Canada.

A plan was implemented to focus product development on a new generation of Fast Rescue Craft (FRC). SAR vessels fitted with both the newer 5.5-m (18 ft) and the older 7-m (22 ft) rescue boat built by CMC had realized the superior seakeeping capabilities of the larger hull and the advantages of the advanced rigid foam sponson technology of the R5.5. By building on technology developed and proven in the R5.5, the design cycle was brought full circle in the development of the new R7 7-m FRC.

Five years of computer system development have brought new efficiencies to welded aluminum construction. In national competition against several GRP and aluminum builders CMC had won a contract to supply five

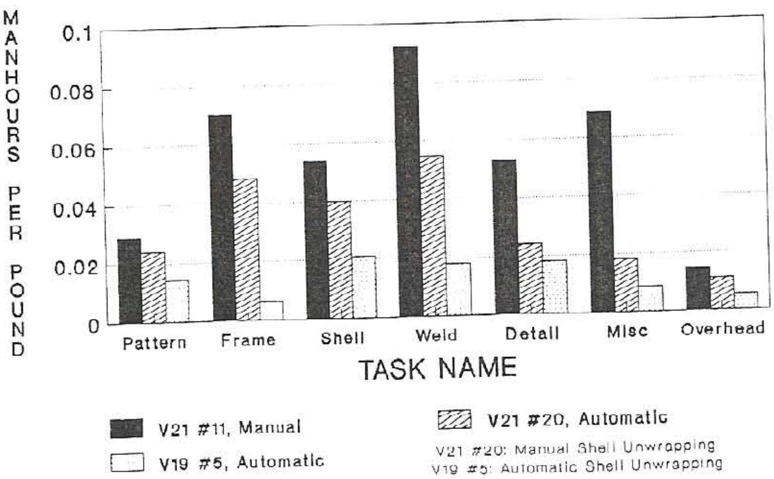

Fig. 9 Manual versus automatic plate cutting, man-hours/lb by task: V21 #11, V21 #20, V19

of a new-generation Safety of Life at Sea Conference (SOLAS) Chapter III compliant rescue craft to the Canadian Coast Guard. This contract was assigned to GSI. With the system installed at the shipyard, including a new HP 319 Unix workstation purchased to replace the poorly supported DOS implementation, work began on the design.

A second aspect of GSI's implementation plan was to provide practical real-time parts drawing and NC programming at the shop floor level to support daily needs in job shop projects and repair work. This was a test of the original system's portability and general functionality. New operators were trained by experienced supervisory personnel, who made the move to GSI along with the computer system. Experience had shown that the skills of the loftsman made him a candidate for successful training in CAD. The original HP 200 RMB workstation complete with drafting and NC postprocessing software was installed in an office constructed in the shipyard's loft. The loft foreman and a tradesman were instructed in the use of the machine, the input of basic part geometry, the drawing and nesting of parts, and the creation of NC code. The NC cutting machine was installed and data communications established with the CAD system. In approximately six weeks an effective basic CAD/CAM system was operational in the previously nonautomated yard (see Fig. 10).

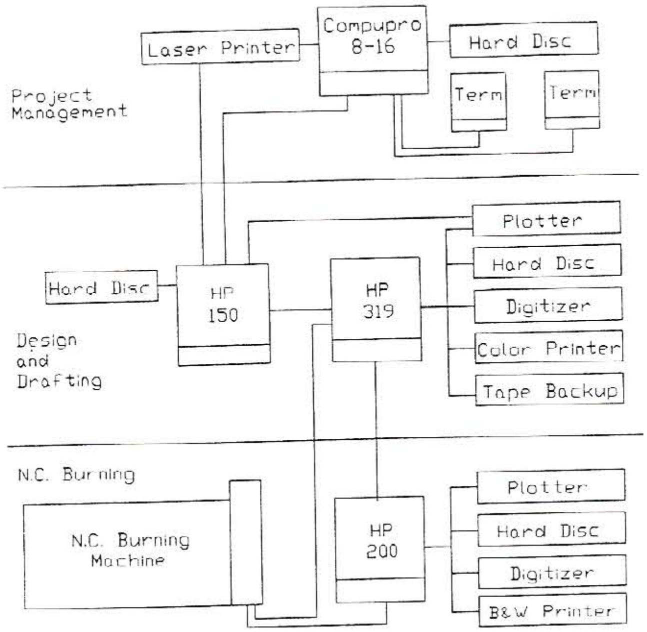

Fig. 10 CAD/CAM schematic (Georgetown Shipyard Inc.)

Initial experience—Excellent yard historical data exist for man-hours expended on lofting and other tasks for a wide variety of projects. Gains in efficiency were easily documented. These have been significant and on a percentage basis have approached those seen at McConnell Marine in the late 1970's with the initial introduction of the HP41. The same toolbox concept has proven equally effective. By putting comprehensible, effective automation tools in the hands of the people already doing a job, gains in productivity are dramatic and almost immediate. Sample data are presented in Fig. 11. Hours for nonautomated procedures reflect the practices of a shipyard with an oxy-fuel optical tracing machine, using white paper templates, nesting each plate on a tracing table prior to cutting. Previously, computer-faired offsets were laid down full size and templates lifted for all plate parts.

Where work now performed by the CAD system has parallels in projects undertaken prior to the installation of automated systems, no attempt has been made to compare GSI throughput levels with those of the previously studied shipyards. Comparisons are between manual and automated methods on similar projects. Where available, actual man-hours are used. In recent cases, where projects have been initiated and completed entirely with computerized methods, projections of man-hours as they would have been prepared previously using manual methods have been used. This has been done only where historic data contain adequate justification to support the estimate.

One project bears some analysis as addressing a frequently heard concern regarding the cost effectiveness of CAD. It is often stated that only in building to standard designs or with repeat orders is CAD justified. There is no question that the ability to reuse data is a major benefit of computerization. However, with the implementation of

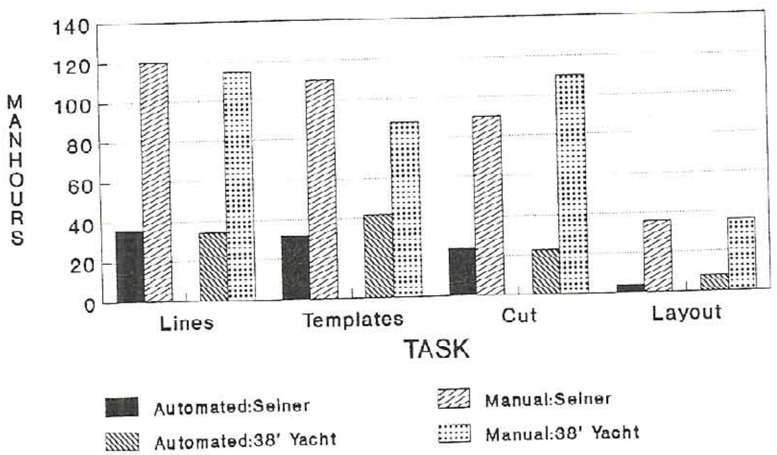

Fig. 11 Man-hours per task, manual versus automated cutting: *Aragosa*, 38-ft yacht; 90-ft seiner sponsons

the appropriate scale along with the right NC production equipment, there are significant man-hour savings available in production tasks in every newbuilding and many major and minor repair projects.

The cutting of structural bulkheads and frames for a major modification and addition to a 90-ft (27.4 m) steel seiner undergoing refit in a mainland shipyard illustrates a routine ship repair project. Pre-cutting of parts was advantageous to decrease the vessel's time on the slipway. Available hull geometry was limited to offsets tabulated on design stations as originally provided to the shipbuilder. Interpolation of data to determine intermediate offsets at the construction stations was done graphically using mathematical splines in the drafting package. With building offsets determined, dimensioned drawings of each part were generated and forwarded to the contracting yard for checking against the vessel. Variations were established to be within allowable tolerances (approximately ⅛ in.) (0.3175 cm). Parts were nested, cut and shipped, preprimed. Figure 11 shows man-hours for drafting, layout and cutting, both as estimated as a manual project and as achieved using basic computer tools. To convey a sense of scale, the labor saved billed at standard yard rates on this project alone would pay one half of the entire 1988 capital cost of the computer system used to do the job. By another measure, the total costs to GSI (labor, materials and direct carrying costs on the system utilized) were less than the cost of the template paper that would have been consumed using optical tracing. Without access to such an NC service, the cutting would have been done at the contracting yard, while the vessel was on the slip, tying up a valuable resource, and adding to the overall costs by thousands of dollars. Pricing of this "enabling" type of service can reflect the value to the client yard of the service rendered. This has been accomplished without the need for lengthy, costly training or the hiring of expensive experts. Know-how already in place has been tapped and simply multiplied through the power of the microprocessor. These are extremely cost-effective systems.

In the implementation stage a mixture of optical and NC burning methodologies has been retained. Part geometry of ongoing projects has been converted to NC code where appropriate through the expedient of measuring templates, manually inputting coordinates, drawing part profiles and nesting in the computer. Time spent on this operation is recouped twice over solely through the increase in travel speed of NC-controlled burning over the limited speed of optical tracing. Moreover, because nesting is required only once for each sheet, there will be no need for re-nesting for the follow-on vessel. The burning machine is not tied up while parts nesting is carried out on the tracing table. That process has been diverted "off-line" to the computer. Access to large numbers of parts in on-line storage while nesting has reduced scrap. Time invested in a denser nest will be recouped again in scrap the next time the sheet is used. Burning of duplicate parts against future hulls, previously adopted to minimize burning machine cycle time lost to nesting, has been eliminated, saving wasted time in transportation of parts to and from storage.

R7 project—The R7 design development project was a departure from recent tradition at GSI in more than just the use of automated manufacturing techniques. Developing the design in-house represented a new and significant step toward optimizing producibility. Design tradeoffs were made from a position more cognizant of yard practices than is possible when design work is subcontracted. The interactive nature of detail design development using CAD was optimized in the case of this multi-vessel order by the ongoing involvement of production personnel in the design phase. Design and drafting CAD operators were provided with immediate graphic access to a whole set of "soft" design constraints such as shop layout and clearances, brake and tube bending tooling, standard yard warehouse items, and crane capacity.

Using the average of man-hours expended per vessel, utilizing NC burning along with other CAD tools developed at CMC, GSI completed the R7s in fewer man-hours than the best hours CMC achieved on any RI22. This was the shipyard's first small craft project. Welders and fitters had to be retrained in thin metal procedures and techniques. Skeptics among the "old guard" had to be convinced of the system's effectiveness. CMC designers, system managers and operators transplanted from a dedicated small craft facility had to become familiar with shipyard practices, formalities and tempo. Because production personnel, although unfamiliar with the specifics of sophisticated small craft construction, were presented with a fully developed design, adapted to their own methods, as well as a complete set of accurate, consistent precut parts supported by detailed production drawings, acceptable productivity levels were achieved over a very short learning curve. Graphed in Fig. 7, the reduction in man-hours over the five-vessel series was in the order of 2 to 1, leveling off quite sharply after the initial two vessels. This was very similar to the experience at CMC. Throughput of metal per man-hour for this thin sheet construction approached the yard's previous average for aluminum ship and superstructure construction.

The R7 program has been through a complete cycle of design development, submission and approval for certification, prototyping, trials, testing and production and is essentially complete. Representing a considerable investment in product and capability development, considerable carry-over to similar small vessels should be expected.

Four each of the V19 and V21 utility craft developed at CMC have been produced, and a new 23-ft (7 m) parametric variation has been developed and constructed. Productivity per man-hour measured either in pounds per man-hour or man-hour per contract dollar has essentially leveled off. Still awaiting installation in a dedicated fabricating shop, the small craft facility suffers from lack of effective raw material and finished product handling capabilities and separation from the main yard support facilities. A dedicated plate burning shop with dedicated material handling is under construction. Throughput per man-hour can be expected to rise 15 to 20 percent with this in place.

The CAD / CAM system has proved capable of performing in a commercial environment. Over an initial 12-month period, approximately 70 percent of the steel, stainless steel and aluminum plate cutting supporting newbuilding (three 130-ft [39.6 m] stern draggers), repair (major modifications to a 120-ft [36.5 m] aluminum ferry) and contracted parts cutting (one 60-ft [18.3 m] aluminum vessel, one 90-ft [27.4 m] steel vessel modification) have utilized the CAD system. The original optical system is now utilized as a backup or where parts are required before geometry has been copied from templates. A plan is in place to upgrade this machine with the installation of an NC control identical to that on the original CMC machine. Lengthening of the original NC machine to 36 ft [11 m] will bring added efficiencies to small craft where shell plates can be full length as well as further decreasing scrap.

Justification

Access to accurate records of man-hours expended, summarized by appropriate task or trade, is a prerequisite if accurate potential cost-benefit analysis is to be done. Most medium and many small shipyards will have these data. Many will have difficulty in finding time and resources to do the required analysis. One aim of this paper is to provide some normalized parameters that have proven to be of benefit in determining the most appropriate scale of implementation. *It is the thesis here that, given the development of micro CAD systems, there is almost certainly a cost-effective implementation for any given manufacturing concern.* It is a matter of—having done the necessary analysis—choosing a system of appropriate scale.

The criteria used in the final system selection should represent a distillation of the objectives of its implementors. The criteria should be general enough to build bridges between disciplines yet specific enough to focus on selected issues. We arrived at the following list:

- system to provide cost-effective measureable improvements in some manufacturing parameter,
- system must be stable and reliable,
- system must be open-ended (a growth path exits),
- system to have potential to optimize benefits arising from being on that growth path,
- secure system support to be available,
- system should be programmable (customizable),
- system to offer highest possible power / cost ratio consistent with reliability and growth, and
- graphics speed to be optimized, consistent with other objectives.

The computer industry prices its offerings according to their potential throughput. A linear relationship exists between power (throughput) and cost. Given this, it is possible to develop a budget for a system by identifying potential tasks for automation, determining throughput requirements to support anticipated production levels and selecting a system with the appropriate power. Some benchmarking may be required to accomplish this if appropriate data are not available. A consultant or input from an objective third party may be helpful. It is as important to select a system with sufficient power as it is to avoid selecting one with too much. Either scenario can be a formula for disappointment, if not disaster.

Only minor variations in price will normally be seen in equivalent competing systems. Some advantage may be gained by study of the position of individual vendors in their product development cycles. This has become particularly evident with workstation pricing in the last year. Dramatic increases in processing power have accompanied new offerings often with decreases in prices over existing less powerful products only a few months old.

There will always be tasks which are the most easily automated. One reason why larger shipyards were among the earliest implementors of CAD is the significant proportion of project man-hours dedicated to geometry definition and parts generation. Together these can approach 20 percent of total steelworking hours, and even higher in the case of aluminum. The cost of rework arising from errors and poor fitup adds another 5 percent. Savings amounting to a further 5 percent can accrue from lower costs associated with better fitup (lower welding and edge preparation consumables) and decreased scrap.

This is combined with the fact that the majority of savings can be accomplished with a simple two-dimensional XY-type of NC machine that is readily available, well proven over many years and with suitable material handling equipment capable of high throughput. There is the potential for a low risk implementation, provided data are available to determine the appropriate scale of system required.

Many CAD system vendors and potential purchasers digress in the study stage, focusing on what the system could do with the application of many high-powered functions, often of marginal profitable use, in the smaller shipyard. The highly competitive nature of computer system sales encourages vendors to focus on features. They may lack industry-specific knowledge required to appreciate users' real requirements. Time is well spent identifying the exact operations to be implemented in software and the best hardware / software combination to achieve this. What is most required is access to extended functionality, understood without lengthy training. These tools are available.

The selection of appropriate drafting software is an important step. The requirement for hull definition and naval architecture software, essential in terms of 3-D geometry and analysis, will be overshadowed by the mundane requirements of steelwork detailing by between 5:1 and 15:1 in terms of man-hour requirements. To realize the true potential of CAD / CAM, the detail design function, previously consisting only of the production of shipyard working drawings, becomes combined with the lofting, template making, and layout functions. The requirement becomes one of developing the geometry and drawing in the computer of every structural part in the vessel to be cut with NC. Gains in productivity come from the draftsman, through the process of design detailing in the production of working drawings, indirectly programming the cutting machine to produce the parts. This is functionally equivalent to his programming the plotter to produce his working drawings through the use of drawing commands in the drafting software. This places a responsibility on the draftsman and the engineering office that they may not have previously had, which points to the wisdom of searching the mold loft ranks for potential CAD operators.

It is not necessary to implement a full suite of CAD and CAM tools. Many steel warehouses now offer computerized cutting services. It is possible and often very cost-effective to job out plate burning. At present there is little agreement among CAD and CAM vendors regarding data and media standards. Some (IGES and DXF) are de facto standards but their implementation tends to be inconsistent. This does not address the further problems of data importation (communications and magnetic media format standards). Those subcontractors willing and able to provide a level of digital access to their systems deserve to be encouraged. CAD systems in service industries may come under the control of the data processing or information systems manager. Their background is as often in accounting or data processing as in the technical fields, bringing with it understandable concerns of data and system security and making the issues of data exchange and format compatibility worse. GSI has been reduced to the most primitive type of data exchange. Shell plates for a 40-ft (12.2 m) steel production yacht were developed, nested and postprocessed on a part-time basis in a matter of ten days. The steel supplier, a major highly automated multi-national firm located in central Canada with advanced CAD and CAM software of its own, manually typed over 36 000 lines of NC code into a word processor attached to their CAD minicomputer using hard copy of the code from our laser printer. The company's policy forbid the installation of data communications software in their computer on system and customer security grounds. The resulting code predictably contained some errors that we caught in test pre-runs and almost certainly minor errors that we did not. It is some measure of the cost-effectiveness of NC parts cutting that even this inefficient method of data input (approximately 40 hr of typing at 60 words per minute (WPM) versus a 30-sec load from floppy disk or a 12-min serial transfer by modem at 1200 baud) was regained in the cutting out of the parts contained in about five 8-by-20-by-9-ft gage steel sheets (about ⅓ of one boat) comparing NC to optical cutting. This is a time saving from the "Patterns" task and cutting speed alone, discounting the differential in rates for clerical staff and skilled tradesmen as well as the overhead associated with the shop space consumed by material while cutting.

Soft benefits

Too much can be made of the so called "soft" benefits of CAD. There are important issues such as production control, consistent quality and increased flexibility, and implementation specific ones such as CAD's potential as a marketing tool. Some are simply hype. Vendors may tend to stress different benefits with ownership and management than with technology implementors and users. *Decision makers must consult implementors to get the full story.* The soft benefits may be saved for closing arguments (where they belong only if hard benefits such as quantifiable cost-effectiveness have already been identified).

It is useful to separate *soft or unquantifiable* benefits, from *spin-off* benefits, arising as side effects of implementation.

The ripple effect will vary depending on the nature of the organization and the implementors. Imaginative individuals will find applications and benefits throughout the manufacturing process. Potential exists anywhere reuse of hard data reduces the potential of error. Access to the geometry database by the largest possible cross section of personnel will optimize benefits. In the entry level implementation this can be as simple as a hull foreman raising his level of confidence in fitup in an area where he anticipates problems through access to a graphics terminal or a full-size plot. Although no attempt is made to justify the installation as a personnel management tool, the applied use of system tools in confidence building can be demonstrated as cost-effective. Rise in morale and associated increased productivity through the elimination of noisy, dangerous, unpopular or uncomfortable operations is measurable. A similar phenomenon arising from positive expectations can also be expected. Parts that fit and projects that go ahead with a minimum of rework and backstepping tend to accelerate on their own with a minimum of prodding. The analogy of the creation of a vacuum ahead of production through the methodical removal of obstacles is an apt one. CAD places controllable new tools in the hands of management for the successful removal of those obstacles.

The discussion to this point has focused on experience gained in the application of computer tools to a closely defined set of tasks. The tools described address the manufacturing problems arising from dealing with the geometry of large scale three-dimensional sculpted and developable surfaces. Traditional construction methodologies addressing these issues have been found to have numerical analogues. Implementing these analogs as numerical methods in microcomputers has been found to be cost-effective. The ease with which this has been accomplished is as much a statement about the exacting nature of the 3-D issues involved as it is about the efficiency of the implementation. It has not taken high levels of integration to realize large gains. Further integration will result in gains through reduction in error and improvements in overall efficiency.

Future directions

In the design office—Removing an obstacle in one phase of a design / manufacture process and accelerating related production will uncover new bottlenecks. Shipyard departments are interdependent. The timing and pace of an ongoing process (department) will tend to be determined by historic needs. With reduced labor requirements for fabrication (Figs. 6 and 9), timely delivery of the exact materials required for fitting out can become the pace item. Many shipbuilding managers will agree that even when a *complete* job description, that is, specifications, drawings, bills of materials and final ship geometry, *exists* prior to project start-up, the availability of the correct outfitting materials where and when required will be the largest factor affecting project performance. Because CAD and CAM tools exist for accelerating and improving the completeness and accuracy of the design description, optimizing performance will require parallel streamlining of materials management. Insofar as it is complete, the CAD database can provide as a starting point accurate, representative bills of materials.

In most small shipyards, contract specifications and working drawings do not constitute a complete description. The required supplementary information contained in requisitions, purchase orders, etc. to suppliers is not consistently integrated into a database. If this database is to grow beyond that required to automate steel cutting, high-speed graphics workstations running highly functional drafting software with methods of attaching attributes to drawing elements will be required. Interfaces with purchasing and accounting software will also be necessary. Shipyard detailed drawing requirements imply that system speed and on-line storage must grow by orders of magnitude. It is this potential multiplying factor in complexity that keeps many yards with potential for savings in steel cutting from implementing larger systems when task-specific tools are what is required.

When pointed, task-specific automation to speed lofting and processing of part geometry has been implemented, can a similar approach be applied to the bottleneck created by the accelerated need for materials? Sophisticated computer programs exist to address these requirements. They have proven to be more difficult to implement effectively than CAD / CAM. Work remains to be done in this area. The approach outlined and proven effective earlier is difficult to apply here. Few shipyards track staff hours by task. Staff may be uncomfortable with a requirement to log time. Even polling staff to identify sources of problems may be seen as threatening. Without man-hour profiles, identifying a task or tasks as targets for automation is reduced to gut feel or guesswork.

Reduction in error is the most likely source for improved efficiency. Completing the job description before starting construction is the most effective method of reducing error. Creation of complete, accurate material specifications, quantities and scheduling requirements in a system able to reuse these data without transcription error becomes a primary objective (Fig. 12). Introduction of CAD and CAM tools for metal cutting can compound problems initially for two reasons. First, the CAD system will provide structural materials to production sooner; hence production will proceed more quickly. Second, systems not accommodating this change of pace will be late in producing detailed outfitting requirements, increasing the likelihood of not having the appropriate materials when required. Time saved in metal fabrication will eventually free up resources and capital to focus on improving materials management.

Beyond the design office—Although the focus has been on completing the job description first, there is potential for cost-effective automation outside the sphere of the design office. Computer-aided estimating, inventory management, project planning and scheduling are examples. The diversity of material coding schemes in use and under development will be evidence enough to establish the difficult nature of inventory management. The continued development of graphics systems with sophisticated functions for assigning textual attributes to graphics entities represents significant hope for more accurate ordering. A completed job description, including mechanical, piping, electrical and outfitting bills of materials with detailed materials specifications attached to graphic entities in the drawing database can be seen as simply an extension of the geometry database in the basic CAD system described earlier. These data can be sorted into formatted tables. This has been done effectively in large-scale systems for some time. Detailed specifications in the form of ASCII text files for out-fitting components should be developed and added to CAD libraries as standard parts. Their inclusion in requisitioning documents would be generated in a fashion not functionally different from the inclusion of the graphics entity in the production drawing. The functionality required for small systems to integrate such data with requisitions and purchasing documentation is not difficult to accomplish, but will require some interface with accounting and inventory software. Current emphasis among system vendors on network ready products is encouraging.

Hardware—Computer hardware is continually improving, both in speed, features, reliability, compatibility, and price. All of these are important issues to the small shipyard.

First, computing speed has a direct effect on user throughput, and the relationship is not simply linear. When a computer responds more quickly to a user's requests, not only is the actual computing finished more quickly, but the boredom and distraction of the user is reduced, allowing greater concentration on the job at hand, and therefore fewer operator errors. Computer software is usually written to be as powerful as possible, while retaining an acceptable response time. This response time, controlled by human attention span, will remain constant. As computers become faster, the next generation of software will be as complex as the computer will allow within this acceptable response time.

Computer monitors are growing in size and resolution, allowing the user to see his drawings and designs at more reasonable sizes with more clarity. This reduces operator fatigue, and also the number of hardcopy plots that must be generated to view the design on paper.

Drafting plotters are becoming faster, and perhaps most important, more reliable. The advent of electrostatic plotters, which operate more like photocopiers than pen plotters, takes this reliability and speed one step further. In the past, the pen plotter could easily become the bottleneck in a design office. This no longer need be the case, as electrostatic plotters can produce in two minutes a drawing that would take eight minutes on a pen plotter.

Mass storage is not bucking the trend. It is not unusual for a user to have 150 or more megabytes of hard disk storage on his system. While this allows faster, more convenient access to data, it requires a new level of librarian skill in the user to keep track of and properly archive all of the data.

A relatively new technology that will make computer-aided drafting easier to justify for many companies is the scanner. This device, along with the appropriate software, will scan existing drawings and convert them to a format that the computer-aided drafting program can understand. In this manner, existing hand drawings can be brought into the computer, for, archiving, library building, further work, or as a starting point for future work.

Software—The design software is continually being improved and fine tuned. More and more analysis functions are being integrated into the design program, such as speed/power prediction, measures of degree of nondevelopability, and detailed, formatted intact and damaged hydrostatics.

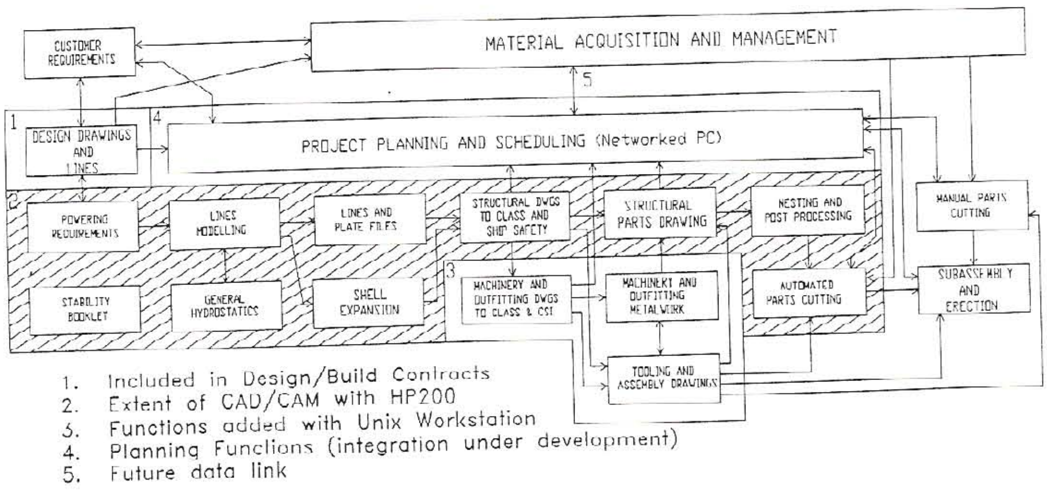

Fig. 12 CAD/CAM block diagram: Georgetown Shipyard Inc.

More complex surfaces will be handled with ease, with added editing functions, intersection and trimming curves. General classes of surfaces will be used to generate components that are pieces of cylinders, cones, or are flat plates.

Better hardware has allowed the creation of very realistic rendering software, where the user controls surface color, reflectivity, smoothness and location and color of light sources (high, white sun, or low, orange sun) for rendering the vessel in the water. This helps not only in the sales process, but in giving the designer a visualization tool he has never had.

Side effects of CAD/CAM

Along with its ability to accelerate production, CAD/CAM brings inevitable side effects, the impact of which on traditional methodologies requires careful management. Implementing system management training, formalized project planning, data certification procedures and other similar functions lessen the potential for disaster from these side effects.

CAD requires a more complete design description

Previously, a crew of shop personnel was involved in the construction process, beginning with the initial laying down of lines. They became familiar with project requirements at an early stage. The project proceeded on an incremental basis. With these tasks moved into the CAD drawing office, the project now moves into the shop with a minimum of prior exposure of production personnel. They will have to be supported with documentation not required previously. Parts coding schemes, subassembly production sketches, reference dimensioning, dimension certification data, etc. will all be required at some level of detail. These requirements do not have to be elaborate. They do have to be accurate and understandable. They will require a mechanism for updating that will give a level of assurance that all parties are working from the same revision. The detail required will be determined to some extent by the immediacy of the access production personnel have to the database. Installation of "read only" graphics devices in the production environment can be cost-effective. Such devices must be "hardened" to survive in the work environment. Such devices are available.

CAD may perpetuate error

Eventually the inevitable occurs. An error which escapes the data certification mechanism propagates quickly through the project. Extreme examples of such occurrences are frequently used by detractors of CAD. There is no question that the cost of such errors can be devastating. A simple example would be the labeling of a nested sheet drawing with the wrong plate specification. The nested sheet drawing is a travel sheet used by production to initiate cutting, marking of part numbers, layout and working of parts such as braking and roll forming. The high travel speed of NC burning is no advantage when the wrong material is being cut. In this example damage is limited to the replacement cost of the incorrectly cut material. More far-reaching consequences could be expected from scenarios where, for example, shell expansion files are generated from one lines revision and section cuts and subsequent structural parts generated from another. Here the error is more insidious, and will soon propagate to where it may be impractical to determine which parts are right and which are wrong. Methodical management of revisions, especially in later going, cross-checking schemes to determine correct material requirements, and formal procedures for production initiation will head off most disasters.

CAD ties up resources

No small shipyard will have sufficient working capital or human resources to satisfy all of the needs of modern shipbuilding. Any capital acquisition will be a tradeoff of long- and short-term objectives. The most attractive options will usually be incremental improvements on proven methodologies. Implementations requiring new ways of doing things will tie up valuable personnel as well as capital. For this very reason a program of simple staged implementation has proven to be the most effective and for many small shipyards the only possible access to these tools.

CAD changes traditional labor/management relationship

This must be appreciated as one of the key issues associated with the introduction of automation. Increased control of production processes by management is rightfully emphasized as a major advantage of CAD/CAM. This extends past strictly technical issues. Labor previously expended in part preparation will shift to assembly. This is appreciated when unpopular tasks are automated. When critical interactive tasks are automated, labor input may be seen to be reduced to the mechanical with a perceived dehumanizing of the task. Labor must be involved in product design and production planning if optimum results are to be achieved. Certain tasks of a highly interactive nature may, although possible to automate, be "better" done by hand. Analysis of machine utilization will determine tradeoffs. At CMC we experienced a level of error traced to the incorrect marking of parts numbers on NC cut parts. Errors were traced partially to incorrect numbering on the drawing, partially to incorrect labeling. To rectify this situation the capability to have the NC machine number part directly was analyzed. Limits on machine travel speed plus the cost of implementing appropriate software to generate character drawing code established the cost-effectiveness of marking by the operator. The error rate was addressed by adding a reconciled list of parts included to the nested sheet drawing. This required the CAD operator responsible for nesting to sign off on the type and quantity of part included in each sheet. The NC machine operator as well must sign off on coding the parts appropriately. By involving both CAD and CAM operators, a least-cost scenario was developed.

CAD blurs design/build dichotomy

The division of responsibility for design and construction as it exists in the small shipyard in North America today is the result of decades of evolution. The placement of a large portion of this responsibility on the contracting yard impacts heavily on the integration of the design and construction database. Some designers will be less than enthusiastic to take on direct responsibility for their data when they are going to be streamed directly into production CAD installations. Their role has been one of providing conceptual data, with the shipyard detailing this to suit their practices. The possibility now exists for this to be greatly streamlined. The ability of the two partners to capitalize on this opportunity will depend on their willingness to cooperate and share the perceived risk. Shipyards may be tempted to move more design capability in house as the power of these tools becomes more available. The benefits of tuning design to suit practices and capabilities have been known and practiced for years. This is simply the next step in that natural evolution. There will be an inevitable tendency among automated smaller yards to look for design firms able to provide compatible digital design data, capable of being loaded directly into their CAD / CAM systems.

Management issues

Evolution of traditional roles

The design engineer and his staff in the shipyard drawing office will find themselves facing a basic decision. The powerful and relatively inexpensive workstations now becoming available will change traditional relationships. Experienced designers can extend their hands-on working career by multiplying their productivity through CAD rather than leveraging their ability with a staff of assistants. Practical construction experience will become more important as responsibility for final detailing moves out of the mold loft and the shop floor and into the CAD drawing office.

Fair compensation as roles evolve

How the means to fairly compensate the computer-aided designer will evolve is not yet clear. Compensation for engineers turned managers is a clear-cut issue. Here the experience, background, credentials, etc. are put to work in managing a team of people. The tradition exists for adequate, appropriate competitive compensation. No such body of precedent exists for compensation of professional CAD, CAM, CAE (Computer Aided Engineering), CAPP (Computer Aided Process Planning) operators. No guidelines exist for their integration into the cadres of managers who continue to operate in traditional formats.

The technology race

Because the cost / power relationship in computing hardware in general and graphics workstations in particular has and will not level off in the foreseeable future, an implementor of CAD will be subjected to a continuing barrage of faster, slicker products. The fear that competitors will zoom by on next year's magic carpet is a source of stress that will be difficult to avoid. As stated earlier, the best defense will be to utilize a portion of savings realized from today's implementation to capitalize tomorrow's.

Summary

Early technical workstations like the HP 9816, its descendants and competitors (Sun, Apollo, MicroVax) have provided a platform for the downward migration of mainframe software used in major shipyards for some time (Autocon, CADDAM, etc.). They have also supported the development of general and application-specific software coming at the problem from the low end. Software capable of solving specific problems in diverse areas has become readily available. Providing a toolbox approach to the hands-on engineer / builder, today's graphics microcomputers and software offer cost-effectiveness over a very broad range of capital investment.

Perhaps the fundamental lesson learned over the past five years concerning cost-effective implementation of CAD / CAM is that it can and should be taken one step at a time. A reliable database must be assembled and studied to find the areas most likely to benefit from automation. An estimate of the savings that can be achieved can be used to determine how big an investment in automation is justified. Some level of commitment from all concerned is desirable. Manpower resources must be properly allotted to bringing the system on-line. Usually this requires a period in which overall productivity drops. This must be weathered to make the system work in the end. To be one, an opportunity must be addressed by available technology.

No unifying vision of how separate software packages are to work together has emerged. Industry standards such as Unix may be emerging for operating systems. Developers continue to some extent to be islands. With rapidly evolving technology they are unable to know where development will take them. They cannot be expected to know your business. It will continue to take a "champion" for applications of technology to take hold in small shipyards. However, as a great American small ship designer / builder, the late Mr. Pete Culler, said, "Experience begins when you start." He was encouraging the potential builder / craftsman to begin where he could and to progress in the scope of his enterprises as his experience broadened and not to be discouraged by his initial inexperience. The current state of microsystem CAD offers a similar opportunity and challenge to the small shipbuilder.

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3 Hays, B. et al, "Hydro-Numeric Design at the U.S. Naval Academy," SNAME, Chesapeake Section, Feb. 1988.

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Appendix

Typical hardware and software configuration for small shipyard CAD / CAM installation

(Brand names and model numbers are given as specific examples)

SOFTWARE: Applicable modules of FAST YACHT / FAST SHIP for small shipyards include the following:

- Professional hull / surface design
- 3-D digitizing / viewing
- Postprocessing (lines drawings and offsets)
- Plate unwrapping
- Intact Hydrostatics
- Planing hull ehp prediction
- Semiplaning hull ehp prediction
- CAD interface
- *Total list price:* $11 200

There are many drafting and NC programs available. Packages discussed or used by the authors are as follows:

Drafting:
- Hewlett-Packard ME-10 (approx. $6500)
- AutoCAD by Autodesk (approx. $3000)
- DGS-2000 by Data Automation (approx. $2500)

NC:
- DCS-2000 CAM by Data Automation (approx. $2000)

Unigraphics by McDonnell Douglas (approx. $16 000, with drafting)

HARDWARE: Two basic types of computers may be used, engineering workstations or personal computers.

Engineering workstation:
- Hewlett-Packard (HP) Model 340C+ color workstation
  - Motorola 68030 processor
  - Motorola 68882 coprocessor
  - 4 Mbytes RAM
  - 16-in. hi-res color monitor
  - Can run technical Basic or HP-UX
- HP Model 7958B 152 Mbyte hard disk drive
- HP Model 9144A ¼-in. cartridge tape drive
- HP Model 33440A Laserjet Series II Printer
- HP Model 7595A A-E size 8-pen plotter
- HP Model 46088A B-sized digitizer
- *Approximate total list price:* $29 000

Personal Computer:
- Hewlett-Packard (HP) Vectra RS/20 Model 100e
  - Intel 80386 processor
  - Intel 80387 coprocessor
  - 4 Mbytes RAM
  - 16-in. hi-res color monitor
  - Can run high-tech Basic, or DOS
- ¼-in. cartridge tape drive
- HP Model 33440A Laserjet Series II printer
- HP Model 7595A A-E size 8-pen plotter
- HP Model 46088A B-sized digitizer
- *Approximate Total List Price:* $27 000