THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS
601 Pavonia Avenue, Jersey City, NJ 07306
Tel. (201) 798-4800 Fax. (201) 798-4975
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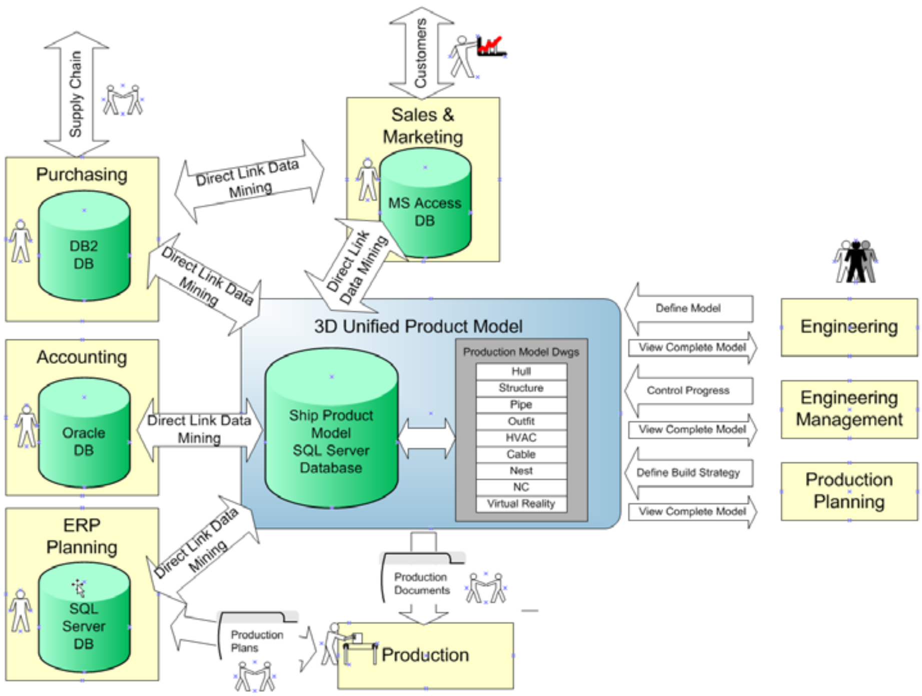
INTEGRATING MANUFACTURING AND LIFECYCLE INFORMATION INTO THE PRODUCT MODEL

Rolf Oetter, Dipl. Ing. (M) [1]
Christopher D. Barry, P.E. (M) [2]
Lawrence A. DeCan (M) [3]
Paul F. Sorensen (V) [4]



ABSTRACT

The power of the Integrated Product Model can be extended well beyond the mere definition of geometry, and this extension offers significant benefits to shipbuilders. The nature of CAD/CAM data allows use of arbitrarily extensible linked databases, which can contain any other information that might be useful for manufacture, production engineering, procurement and even maintenance and operation of the ship throughout its lifecycle.

[1] Albacore Research Ltd, Victoria, BC.
[2] U. S. Coast Guard Engineering Logistics Center, Baltimore MD
[3] Littoral Research Group L.L.C., Metairie LA
[4] Object Technology Information Specialist, Inc., Slidell, LA

Information technology is … an ***essential enabler*** *… permits companies to reengineer business processes*
Hammer & Champy (1993) [1,3]

INTRODUCTION

The computer based ship Product Model has been widely accepted as the best way to approach the problem of defining geometry and similar aspects of design, but the flexibility of CAD systems and linked databases allows extending it in many ways to improve productivity, quality, reliability and maintainability.

Manufacturing data, especially group technology process resource classification data (traditionally part coding) and scheduling and management data, can be coded into structural, piping or other fabricated part data and this information can, in many cases, be automatically derived from information used to define geometry. Procurement and non-geometric interface ordered item data such as pricing, delivery date, flow or electrical connection interface data, and testing requirements can be linked to objects representing outfit items, and the product model can be used to locate information in these databases by using the product model as a navigation tool. Finally, the procurement and interface data can be used, and enhanced, to provide long term logistics support information, and aids for training and emergency response.

A Product Model is a database or set of linked databases that defines the ship to the extent desired by the users and developers of the model. Prior to the invention of orthographic drafting, the Admiralty model was a physical scale model that was used as a key contract "document" to define ships to be constructed, generally actually using the same materials that the ship was to use, but at a greatly reduced scale.

Conventional paper drawings then took over the main role of defining the geometry and other features of ships to be built, but much of the capability to readily envision and understand the final product was lost, since drawings have to be interpreted.

Conventional paper drawings were then produced using Computer Aided Drafting (CAD). This is not a true product model, but even then, the use of data linked into the drawing had begun. AutoCAD offered "attributes", arbitrary text or numeric data linked to blocks representing components. The archetype for this was examples of phone numbers linked to symbols of telephones in an office arrangement drawing.

This use of extended databases has revolutionized the use of CAD and databases, especially in the area Geographic Information Systems, which links CAD maps, databases of features such as property definitions, tax payments or any other geographically identifiable data. Similar drawing/database hybrids are used to manage shopping centers, linking tenant business information and drawings. It has even been said that more existing oil refineries are being redrawn in CAD to build management databases than are being originally drawn for new construction.

In the marine field, the ready availability of three-dimensional CAD, combined with the needs of Computer Aided Lofting/ Numerically Controlled Cutting fostered the development of three-dimensional models, especially structural models. The requirement to manage the piece parts resulting from these models, and the need to automate the routine but tedious processes of extracting information for numeric code development fostered development of automated tools to build the model, to extract data from the model in various formats and to link data both to databases from the model and in reverse. Jolley (1992)[5] gives an early example of automatic drawing editing from a database. He developed a system to automatically draw stiffeners in an AutoCAD R10 drawing from a DBaseIII stiffener list that was originally derived from the AutoCAD drawing. Any changes in the database due to design development were fed back into the drawing automatically. End cuts and similar features were also automatically derived. Mercier (1997)[8] illustrates a hybrid 2-D 3-D system that automatically derives and inserts structural weights in an internal database.

Each of these steps (and many more) has brought us back in a circle to a true, three-dimensional model, though now in virtual reality rather than small scale. The model also has substantial non-graphic, or non-geometric information either internal to the CAD file or dynamically linked to it.

There are substantial advantages to the 3D Product Model compared to paper drawings or even CAD drawings. First, of course, the geometry of the model is exact, inherent and three-dimensional, so measurements are reliable and unambiguous. Also, since there is only a single depiction of any given system or component in the files that make up the product model, there is no possibility of conflicts between drawings. Finally, the inclusion of non-graphic data increases the richness of the data included in the model.

These elements are the minimum features distinguishing a 3D Product Model, from a collection of CAD drawings, or even 3D CAD models, and it is important to understand this distinction before moving on: Though a Product Model may provide more or less conventional drawings, the drawings are views of the Product Model, (usually automatically derived). They are not themselves the Product Model. Such models can be either a single massive file, or a series of linked CAD files, but as long as they are set up so that each

[1] Superscripts refer to reference tables

component is uniquely defined once and once only, and that it is possible to interrogate and view any component or combination of components through their linkage, the essential advantages of a basic Product Model are obtained: the product geometry is fully and unambiguously defined and readily accessible.

This definition may leave an initial impression that massive files are somehow superior to linked small files, but this not the case. The concept of linked files, especially in the context of an open system, is actually considerably more powerful, because it allows endless opportunities for extensions.

Once the basic geometric model is achieved, the next steps in improvement are to go beyond simple geometry and add linked data, and the extensibility afforded by an open system is optimal: Linked databases in an open system allow connecting, accessing, and using data in a wide variety of ways throughout the vessel construction and subsequent lifecycle. In addition, the capability to link arbitrary databases allows the model to be extended long after the initial design of the core databases, in ways the initial database designers would not have anticipated. This is not possible with a definitive massive file system.

We would like to begin by suggesting a few possibilities that will improve productivity and business processes, beginning from those requiring minimal effort to increasingly complicated extensions. We will also suggest uses for the database subsequent to delivery of the ship. However, it is important to note that these are suggestions, and the key idea is the essentially limitless extensibility inherent in an open system comprising linked files.

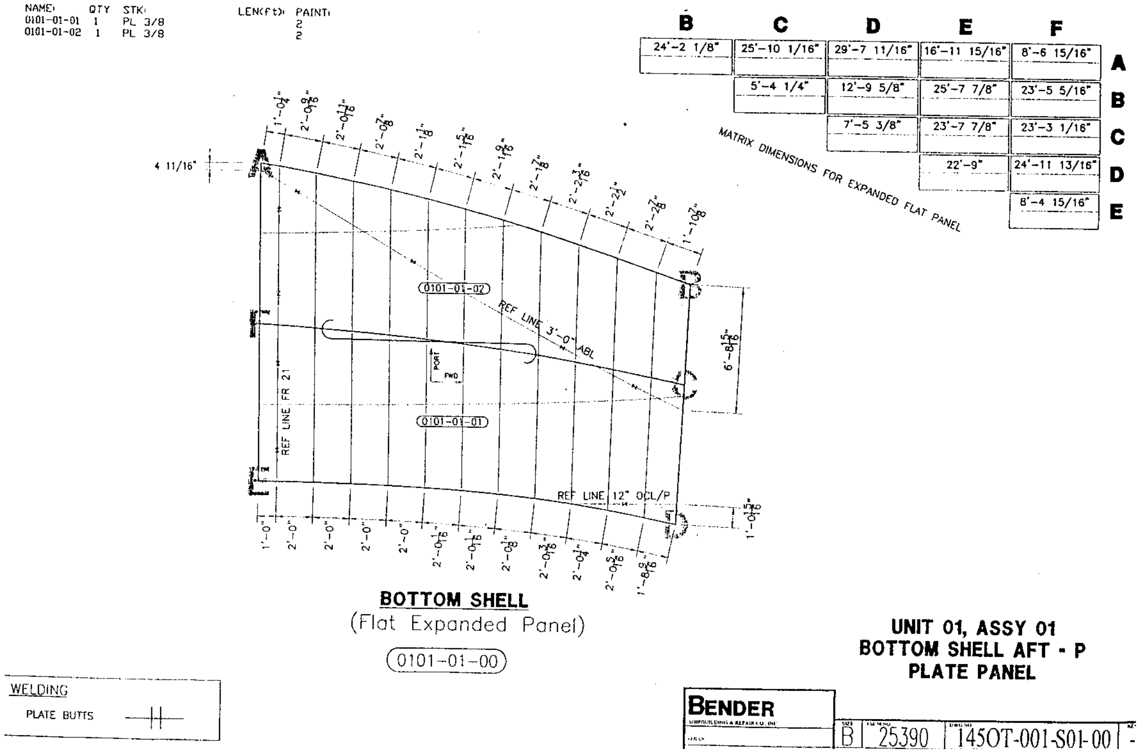


Figure 1 - Work Sketch

The authors would like to note that their experience is in the AutoCAD and SQL database environment using the Ship Constructor system (which includes ShipCAM as a primary hull definition tool). This paper discusses some specific techniques in terms of this software and its nomenclature as an example, but the authors recognize that other packages have similar features and capabilities.

WORK SKETCHES

It is worth examining the first step in how the basic model can be used in construction through the key concept of “viewing the model from different angles”, especially because it puts aside some common objections to the product model and produces very real improvements immediately.

When builders initially encounter the concept of the product model, especially when it is demonstrated with very impressive color renderings in virtual reality, they often object that this kind of data is unusable on the shop floor for a variety of reasons. This impression is correct, but the ability to view a product model as needed by any work process can be provided by the software system. Figure 1 is a typical work package sketch. It shows a step in the construction of a module and provides exactly, and only, the information needed by that particular work "pallet". It has the bill of materials required to accomplish the work, so physical palletization is readily accomplished, and it provides data to layout and optionally to record any dimensions needed. The exact nature of the product model, the fact that any component is defined only in one unique place and the capability of CAD systems to have dynamic dimensioning (automatically updating any dimensions derived from changed geometry) allows "redundant dimensions". These redundant dimensions can be extracted and presented in the most convenient fashion. Workers need not root through sheets of drawings or make calculations to determine any dimension needed, and this probably saves as much rework due to error as it saves time in determining dimensions.

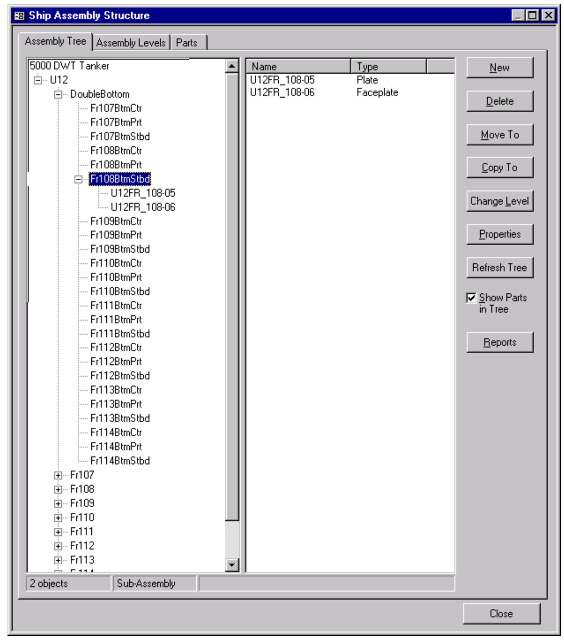


Figure 2 –Part Tree

MODERN MANUFACTURING TECHNIQUES

Modern manufacturing systems are frequently defined in terms of the famous Toyota Production System of Ohno (1978)[10]. Features of these systems include *kan ban*, part coding, Just-In-Time, statistical control of production, *kaizen*, manufacturing cells and 5S.

Benefits from these systems are generally:

- Optimum use of resources
- Just In Time procurement
- Accurate bidding
- Meeting schedules
- Continuous improvements in productivity
- Maximum use of appropriate automation
- Improved accuracy and reduced rework

Extending the product model databases can facilitate all of these, except perhaps 5S.

KAN BAN

First consider *kan ban*. This is pronounced "con bon", which has also been used by Harmon and Peterson (1990)[4] as a mnemonic acronym for "Card Out Notice" and "Build On Notice", which describes well the two cards used in one typical mass production oriented system. The term means "signal card" in Japanese. The classical *kan ban* system uses one or two cards attached to an interim product. When the product is moved to the next stage of processing, the cards are returned to earlier stages, thereby signally the early
stages to replenish the supply of this product.

Because *kan ban* is associated with repeated replenishment of a repetitive product, it has not been widely considered for shipbuilding. However, *kan ban* variants are widely used in "high mix - low volume" manufacturing, (Mahoney, 1997)[7] where a low volume of each of a range of highly varied products are made, usually to order.

The generic high mix - low volume one card system uses a conceptual card (either a physical card or some other signal, such as a spot marked on the floor or a marked physical pallet) linked with an interim product. Completion of the pallet on the interim product results in return of the card to the previous work process, but instead of producing an identical product, the card is a signal to advance one stage along a predetermined production order assigned to that particular station. For example, an empty physical pallet presented at the burning table would be a signal to cut the next plate scheduled for the table and load the contents on the pallet. Unlike a mass production *kan ban* card, a generic card does not direct a particular package be accomplished, but only the next one. This could be modified slightly by having multiple parallel schedules, each triggered by a particular type of "card" – a green pallet might trigger producing to and incrementing a work schedule associated with one grand block, while a red one, work associated with a different grand block.

Use of the generic one card system requires that a work order be available. Fortunately, work order data is contained in typical work tree information in the database associated with the product model. In this tree (generated as the product model was defined by the designers), piece parts, are built into assemblies, which are built into modules, and so on, forming an inverted tree. Figure 2 shows a typical part tree from a ship construction database. It is trivial then to transverse this tree and develop a part order schedule, especially since it need only have the most approximate timing data associated with it.

Suzaki (1987)[11] shows another system called a "*kan ban* sequence table" that could also be considered for ship production. This uses a board with three rows in different colors, red for highest priority, yellow for less urgency and green for other priority, and columns for product type. A returned *kan ban* is put on the left side, in the row indicating priority and cards to start new work are picked up from the far right, red row first. For shipbuilding (with few identical repetitive work packages) this will have to be changed a bit. Instead of a retuned card being placed on the board, it just signals pick up of the leftmost pallet (work package). Work packages are placed on the board as required by production needs, which serves to ensure that the work doesn't get out of sequence. The placement of cards will be directed by the information in the product model based on sequencing the part trees, and feed back from the returned work package cards, rather than by simply rehanging returned cards as in the conventional system. The returned work package card information would be fed back to the management software (driven by product model data) to derive modified sequences. This data would also be used to provide accounting data on actual time and labor for each work package.

One possible system specific to shipbuilding is the "clipboard" system. Real clipboards are marked specific to a given process, such as the CNC cutting table. When parts are cut, the kit instruction for using those parts is passed on the clipboard to the next stage with the parts. When the next stage is done assembling them, part of the instruction sheet is torn off and filled out with labor hours and other statistical data and set for collection. A new instruction for the next stage (from their *kan ban* sequence is put on a clipboard for that work stage and the empty cutting clipboard is returned to the CNC table, which meanwhile has picked another work instruction and clipboard off its *kan ban* sequence board.

The point of any *kan ban* system is that work is pulled through the system by end stage demand rather than being pushed. This results in "just in time" production, reduced interim product inventories, which due to the bulkiness of most shipyard interim products, means greatly reduced labor in handling. Use of *kan ban* also reduces scheduling effort by management, since in general, tasks need only be ordered correctly, not timed. With a motivated, cross-trained workforce, *kan ban* will also allow workers to speed up the schedule, because they will not wait on work.

At this point it is also becoming clear the interrelated nature of each technique – controlling pallets by *kan ban* is certainly enhanced by developing pallets through use of work sketches and other data derived from the product model.

GROUP TECHNOLOGY

The next easiest step is key to group technology, which requires classing products by the required processes, problems, resources and (in the case of shipbuilding) the location of an interim product. Clearly, locational classification is inherent in the product model. A location of interest can be viewed with all systems present, even if each was defined system by system.

Each system will have been designed separately in a "right of way" – each system is assigned a volume that it is guaranteed sole access to. These volumes are simple in the initial stages and develop through the cycle – in general some systems will grow and other shrink, but because the right of way is known, it can be reassigned and adjudicated as needed. In essence, this is somewhat like modern "top-down" software design; modules are initially envisioned as black boxes and only their interfaces are defined, then each is designed internally with confidence that they will eventually link up.

However once they are in the product model (generally as an "external reference" in AutoCAD – a dynamically linked CAD file), they all appear in space in their correct location. Any interferences can be resolved, optimal order of installation can be determined, and opportunities for improvements such as combined pipe hangers can be identified.

During design, an appropriate software system, or the operator, can link process and resource requirements to the parts.

Process requirements include what sort of processes the part will undergo, and this will require equipment and labor resources: a structural piece part may be cut to length only, cut with special end treatments, computer cut to a two dimensional shape, cut and flanged, cut and rolled, cut, rolled and line heated, welded up out of smaller raw stock and then cut, etc. An assembly of piece parts may require a variety of different levels of welding effort, some of which is more difficult than others and may weigh such that it requires various sizes of lifting equipment to handle.

This identification of resources and classification serves several goals: First, it identifies opportunities to establish "work cells" – dedicated shops to produce related products, organized by product rather than processes, combining all needed processes in a cell. (This is often cited as the main purpose of part classification in mass production.) In shipbuilding, cellular manufacturing is an especially good opportunity because cells mainly consist of worker teams with simple tools rather than elaborate machines, so establishment of cells or "people modules" (Turner, 2001)[12] is very easy.

Second, it allows scheduling the resources, and determining and optimizing future needs.

Third, it allows, with other techniques, identification of potentially common or related parts.

Finally, the combination of process data and work quantity (which is inherent in the model) allows leveling work packages as to content and schedule time. This allows use of cycle ("takt") timing concepts to synchronize work, eliminates "crunches" at the end of a production period, and allows a stable labor force, without overtime or layoffs. In the case of ship construction, short, equal time periods for defined work packages minimizes the opportunity to shift and hide overruns by transferring costs to long-term work packages.

A small example is of interest here. One of the authors was asked conversationally by a shipyard about the wisdom of buying a piece of equipment mainly dedicated to making reinforcing rings for beam penetrations for piping and electrical wiring. They were spending a couple of man-hours in welding and on a general-purpose press brake to make each one. Unfortunately the yard had not done its homework in this regard and was unable to determine how many of such rings they used, what range of dimensions they were, how much they cost, or any other quantitative data about them. If this data had been available, the decision would have been obvious, the range of options would not only include purchase of a machine, but changing design policies to eliminate rings of certain sizes, and outsourcing the rings to a specialty manufacturer, who would then be able to make a few standard sizes for a few dollars each. Without this data, even the decision to buy the machine was unsupportable.

GROUP TECHNOLOGY FOR STATISTICS

Finally, and of critical importance for shipbuilding, when combined with statistical analysis of production, and data on parameters of the piece parts, productivity can be compared with difficulty to make. (More on this below.) This means that bidding can be more accurate, improvements can be identified and alternatives in design can be compared for cost and schedule.

In the machine shop industry, elaborate part coding systems have been developed for the exact purpose of classifying parts in terms of the resources they require and the difficulty of producing them. Similar systems have been proposed for both piping and ship structural steel, and presumably a designer could class a part and enter it with its part number, though use of these systems does require substantial training.

However, use of a database, rather than an explicit part code, allows greater flexibility and is probably simpler. Harmon and Peterson (1990)[4] note that they were approached by Harley-Davidson to analyze a machining cell after an expert in part classification had analyzed the process by part coding for six months and had determined the products were too varied to cellularize. Harmon and Peterson instead used a group technology matrix, simply a chart with rows for parts and columns for machine tools, and a check in every square for a tool operation on a part. This process took a few days and resulted in a successful machine tool cell. The database is well suited to generating this sort of matrix, and it completely avoids any translation of processes or sizes into a part code – the processes are linked to the part in the database.

This also allows use of another concept that has interested the authors; in some cases, part characteristics are definitive – a part is flanged or is not and it can be considered to be a member of the set of flanged parts or not. In other cases though the characteristic is not defined by hard lines, it is fuzzy – access to weld is easy, difficult or very difficult and a part can be considered a member of the set of easy to weld parts to some extent, and difficult to weld parts to some extent. Fuzzy logic (Kosko, 1999)[6] is a new tool for dealing with this type of data and has proven to be extremely powerful. In the case of a structural part, a rule that easy welds have a 30% weld factor but difficult ones have a 10% weld factor can readily determine an effective weld factor for welds that lie between the two extremes.

One more aspect of accuracy control data and the product model is worth noting; as built data can be fed back into the product model to determine need for rework, accuracy goals for rework and possible alternatives. If a component comes in exceeding a dimensional tolerance, it may be possible to modify a dimension on a component that has not been built rather than reworking the bad part. (Obviously, use of the product model also allows rational determination of dimensional tolerances in the first place.)

WEIGHT

Weight is an important characteristic of parts in shipbuilding for several reasons. As noted above, weight handling requires time and resources and sometimes the resources required are in short supply or otherwise constrained: A given crane may only be able to lift in certain circumstances or over certain places. Constraints on lifting are often responsible for non-optimal divisions into modules, and in some cases it may be wiser to assemble a module with smaller parts that could be handled by forklift than to pre-make larger parts than can only be handled by a crane. The merit of independent data rather than a standardized coding scheme is clear here; a standard system could not take into account the available lifting resources in a given shipyard at a particular time.

Weight information for particularly large items such as grand blocks is also critical in managing the lift. Not only must the weight be known for safety purposes, but its center as well. This enables placement and design of fittings to make the lift. If the fittings are well placed, effort in rotating the part to the landed position is minimized and with it time and labor is reduced and safety is maximized.

Finally, knowledge of the weight of a module and the weight of the parts it contains (and hence how finished it is) allows weight control during construction, which is often critical, especially for high speed craft or offshore oil systems.

STATISTICAL CONTROL OF PRODUCTION

Statistical control of production is the measurement of product "quality" features, especially labor to produce (this may not be normally considered a quality feature for an end product, but it is certainly one for an interim product). Other features might include accuracy and weight. In theory all of these features are predetermined, but statistical control measures them, thereby determining the range and variance of these features. This in turn determines whether the process producing them is in control, whether efforts to reduce variation are successful and so on. However, these features, especially cost to produce, vary depending on the product made. Unlike most manufacturing, shipbuilding interim products are rarely exactly similar, so variation could be due to uncontrolled aspects of the process or due to design variations of the product; excessive accuracy variation could be due to more welding or more difficult welding required on a part rather than variations in the welding process itself.

The role of group technology information in the product model database is clear here, it distinguishes parts by the processes required and provides essentially qualitative information of the requirements of a work package. The product model also includes many quantitative features for a given work. It includes weight, perimeter length, and part count automatically. Some software also explicitly has designers mark weld paths, or automatically derives them from knowing the contact between two parts. This gives data on the length of weld, the weld type and so on. All of this can be readily extracted from the model. With both quantitative and qualitative information, the statistics gleaned from measurement can be related to all types of input, and sources of variation can be analyzed. This will facilitate bidding accurately, as time can be more accurately related to the type of work to fine tune measures such as manhours per ton.

Statistical data is also important for managing workforce needs. There is a growing shortage of skilled labor in the metal trades (Bell, 2003)[2], and training and similar longer term manpower planning issues need good data on worker productivity and required skill levels for planning.

Probably much more important though, this information guides continuous improvement, (*kaizen*). It is fine to improve processes so they are faster and more accurate. It is also wonderful to design products that can made more easily, (both is best) but it is important to know the difference.

One very simple example here; a small shipyard carefully tracked the cost of seam welding plates to optimize plate ordering and thereby knew the labor cost of buying, for example, longer, but generally more expensive, plates that required less part seaming, or "bargain" short plates left over from someone else's order.

AUTOMATION

Automation is often a holy grail of manufacturing improvements. However, the equipment can be expensive, and worse, programming the equipment requires a great deal of time. In the case of shipbuilding, with few repetitive tasks, the effort to program a welding robot, for example, is often more than it saves. However, the product model can include welding data, which is readily extracted from the model and transferred to robots, just like cutting data. This can be more difficult, as clearances of the devices around other structure needs to be considered as well, but the data needed for clearing other parts is available in the same system, and are used in essentially standard "collision detection" (literally in this case) algorithms.

AutoGen is a typical application; it automatically generates robotic path and robotic weld data when presented with part geometry in computer work cell using rules based information including MILSPEC or AWS standards. The application also features work cell environment awareness and generates paths for cross-platform robotic applications using information that has already been tagged on the CAD model.

It is also important to understand appropriate levels of automation. Automation is expensive and heavily dependent upon upstream operations to insure part quality. The use of statistical analysis of production and quality against product features allows finding data on the production bottlenecks and addressing (and subsequently measuring) opportunities for automation.

Welding automation is a good example. Robots can be a good deal simpler than might be imagined. A "weld pacer" (known as "Bug-Os" or "Moggys", based on two common brand names) is essentially a motorized clamp that crawls along a stiffener, pushing a GMAW torch. The characterization of weld paths and subsequent measurement of welder productivity will identify opportunities where such devices can be used profitably.

These devices are simple to program, generally through dial settings on the machine, but even these settings could be automatically derived from the product model, and listed on the work instruction. The level of programming possible with these devices is also becoming more complex, such that it will soon be worthwhile to be able to generate and transfer programs directly from the product model.

Another simple automation possibility using the data in the model and the assembly tree is automated part pick and sort. The burn sheets "know" where each part is. This data can be used to drive electromagnets at the end of z-only axis arms on a gantry to pick cut parts off the table and then sort them into pallets (both physical and conceptual) beside the table. Such "pick and place" robotic applications are routine in mass production manufacturing, and since the data to drive them is inherent in the burn sheet, it is a trivial development. The assembly data would allow multiple pallets to be cut out of one plate with minimal hand labor for sorting and greatly improved accuracy, and the parts could even be sorted in optimal use order.

Note also that use of bar codes (again automatically generated within the product modeling software) would greatly facilitate any of these schemes. Bar codes could be stuck on labels, or could be marked with zinc jet, ink jet, laser, or electrochemical discharge prior to burning the plate.

DESIGN/CONFIGURATION MANAGEMENT

In a perfect world, the design is complete before any construction is done, and it is correct. The real world is not so perfect and design proceeds during construction, as changes are made. Design changes during construction are possibly the major source of rework during construction, and almost certainly the major source of overruns. The product model allows better integration of changes and ensures that changes may automatically, if appropriate, propagate through the design. Past experience has shown that automatic propagation should be selectively applied, as side effects may result in unintended global changes to the product model. Nonetheless, this is an instance where adding data to the product model beyond the geometry of the design offers substantial benefits.

Version tracking data provides control of parts, assemblies, section, and entire vessels, including proper versioning of production tools, jigs, fixtures, and processes.

Version tracking can interact with the model to constrain visibility of "parts" through a "view", which is filtered by a predefined label, date/time, version number, block number, baseline, etc. The idea is to be able to step back in time in a controlled manner to look at the configuration of a part, assembly, section, or even an entire vessel.

Likewise, the production facilities, models of tooling and arrangements (both as-designed and as-built) used to construct the vessel could, when placed under product model based configuration management, provide the data needed to fabricate a replacement part for a 30-year old vessel. Since the tooling designs needed to accurately manufacture the replacement part for that particular vessel can not only be "found" (which would normally not be an expectation of the vessel owner), but may be electronically transmitted to any location in the world with the capabilities (and clearances for national security vessels) to build the part in a timely and cost effective manner.

Furthermore, during, and at the completion of the vessel's construction, any electronic medium, such as digital photographs, laser scans, dry dock positioning, and subsequent versions of these can be managed through retention in a configuration database along with the part data and linked to it. This latter information can then be put to good use when a system on the vessel or the vessel itself is damaged, since the appropriate version of the part or system can be recalled and compared against the original or appropriate previous modification to assess the amount and shape of the damage, by applying differential analysis between the two models, thus rapidly decreasing the amount of time necessary to plan and design the repairs.

Traceability is the ability to understand why a change was made. Since this type of information is not in any predictable form, it must be independently linked to avoid either endless extensions of a standard or dropping data as required to fit a provided tag. Though this sounds like merely an opportunity to provide blame, (which might be worthwhile in some contracts), ready traceability provides an ability to trace the progeny, rules, regulations, and decision path/tree for why a particular part or configuration was used in the first place, while tracking any regulatory or operational decisions as to why the part was modified, removed, replaced, etc.

In one case, a particular weld size 25% larger than normal was used on a fillet weld as per contract. The contract had initially been modified from the standard AWS specifications for no currently known reason. The additional weld size resulted in excessive heat input and resultant plate distortion. Since no documentation could be found after a thorough investigation to establish the reason for the increased weld size, the management's decision to reduce the weld size to its normal value as specified by AWS, instead of continuing with the larger weld size, introduced greater contract risk than if the original decision to increase the weld size had been documented in the part model in a manner that permitted traceability back to the original contract specifications. Obviously, traceability back to the MILSPEC or operational requirement that engendered the original weld size increase would have been quite valuable.

The decision to reduce the weld size to its normal value could then be added to the traceability information contained in the part model to provide future traceability should the reduced weld size come under question due to unsatisfactory performance of the joint.

Since the entire lifecycle history of the part is stored in a configuration managed database, all modifications to not only the part, but the language in the contractual document, and the regulatory documents calling for the change, are available for review by management and customer representatives at a later date, especially if this particular part should be embroiled in an admiralty or contractual dispute. The readily available archival traceability information also enables further efficiencies in procurement, maintenance, scheduling, and material handling.

An example of off the shelf applications that support this level of traceability and version control in the software development field are the IBM Rational Enterprise Suite and ClearCase UCM product lines.

The MultiSite feature of the IBM Rational product lines allows controlled sharing and replication of defect, workflow, and versioning information to one or more sites across the country or the globe in a predictable manner, whether connected via high-speed data link, e-mail, or even physical media like CD-R or DVD-R delivered via overnight package or national postal service. RequisitePro provides Requirements Traceability using widely available office productivity software like MS Word, and databases like Access, SQL Server, or Oracle, to allow insertion, tracking, and maintenance of traceability hyperlinks. These links, which may be embedded in the original source documents, or in a controlled copy of externally provided documents, provide a way to trace between regulations, specifications, contracts, and production processes to track why and when decisions, change orders, and modifications are made. Windchill is a similar product and is currently in use in collaborative shipbuilding environments.

By utilizing the built-in programmatic interfaces provided by standard off the shelf word processing tools like Microsoft Word, the open product model databases may be queried at will to generate highly customized and formatted documentation suitable for direct submission to vendors, contractors, customers, and regulatory bodies. (This approach was found to be quite successful on the Space Station Freedom Program, where government deliverable documents were generated by the contractor directly from a mass properties database into the designated technical publishing system with all required formatting and markup already in place. A more recent example includes automated production of the NIMA Notice to Mariners publication using SGML and Adobe FrameMaker. The recent addition of XML capabilities to MS Word brings this functionality to the mass market.) When combined with the traceability information residing within the product model, supporting documentation may be readily generated to substantiate why, when, and where changes were made.

It perhaps goes without saying, too, that if the process of configuration management is easy, the probability that the drawings represent the ship is increased and the cost of making as-builts and maintaining them is reduced.

PROCUREMENT

The extensibility of the databases linked to the product model has manifold benefits for procurement, especially when also linked to work packages and the schedule derived for *kan ban*. This is especially important for changes. As the designer selects parts, the key interface attributes can be identified and inserted at the interface points of the system. This can not only increase information, but can reduce drafting effort – it is probably easier to just mark a point and attach text based fastener or pipe connection information than it is to draw a hole and even insert a fastener model, much less draw one. The extraction of bills of material is completely automated, and databases from each system can be compared to find opportunities to reduce part count. Since the linkage is two-way, substituted parts can be readily re-inserted in all the appropriate places, and the places will all be flagged to check the functionality of the replacement in each case.

With a database of part numbers, procurement data such as price, vendor and delivery date can populate another database, and the ordered and received information can populate yet another. All of this is linked to work packages to ensure that the parts for a package are available before three fitters and an outside machinist are standing around with puzzled looks, at a combined rate of two hundred dollars an hour.

Weight data can also be maintained for purchased parts and fed back into the model. In weight sensitive ships, weighing components is easy, but without a database, feeding the as-weighed data back into the model reliably is very difficult.

BUILDING AN OPEN PRODUCT MODELING SYSTEM

The shipbuilding and other industries have seen many product modeling systems in the decades past. In general these systems can be associated with high cost for the software license purchase and high cost in training and re-training. Most importantly, these systems are completely based on proprietary software modules, which make integration with any outside software systems either impossible or cost prohibitive.

An open product modeling system is based on industry standard CAD and database platforms.

A product modeling system stores all CAD geometry in a large number of CAD drawings, while all data associated with the drawings, parts, assemblies etc. are stored in the database. Every part, every drawing, each piece of raw material each revision of each nest are tracked using the central database system. The relationships between the different tables are most often constructed using indices. However, a much more flexible approach is to link all records together using global unique identifiers.

A GUID (global unique identifier) is a term used by Microsoft for a number that its programming generates to create a unique identity for an entity such as a Word document. GUIDs are widely used in Microsoft products to identify interfaces, replica sets, records, and other objects. Different kinds of objects have different kinds of GUIDs.

GUIDs together with procedures to solve conflicts allow product model databases split into two or more copies, be modified at different locations, and be merged at any given time. This allows yards and designers to cooperate on a single project without the need to have high-speed real-time data connections to the same central product model database. A typical implementation of this is shown in the frontispiece.

ShipConstructor is a typical open Product Modeling System. It is based on AutoCAD and an SQL server database and using the industry standard CAD and database linking system lowers the cost of operation significantly.

Most designers, engineers and drafters are versed in the use of AutoCAD. Many even have had some exposure to MS Access, a low-end database system. It has been proven over and over that a small mom-and-pop shop can economically use the same software tools for the production of small vessels, as can large yards assembling more than 50,000 parts to structure with more than 10,000 tons in steel weight alone.

This is facilitated by the use of special tools, residing within AutoCAD and using the well-known AutoCAD core programming features to automate many otherwise difficult modeling tasks. For example, most drafters are used to working in 2D, and the translation of planar representations of components into 3D objects is unambiguous and straightforward for software, so the designer works in 2D in the system. The tools automatically translate the 2D edges of plates, for example, into 3D solids, flange them on command, extract the edges into separate files for subsequent nesting, and so on. None of these tasks require any design decisions on the part of human beings, they are just exacting, picky and tedious, and software is ideally suited for exacting, picky and tedious repetitive tasks.

In the case of piping, the designer prefers to think in terms of pipe and fittings, not lines and circles. The combination of software tools and parts libraries allows the designer to build a model in his own terms and the software translates a command to place a fitting as instructions to insert a block (with attributes) from a library. The fitting has data that allows a pipe line to be generated that fits it – the software know what size pipe the fitting fits and can generate it automatically along a simple line requested. The software won't allow a tube fitting to connect to a pipe, and can send all the pipe length, weight and other data to any other databases.

An open Product Model System provides the great opportunity to combine the many existing disparate island solutions, such as sales, purchasing, accounting, and planning with the product model to one highly effective organism. Most systems used in the various departments are usual based on one of the major SQL compliant database engines, such as IBM DB2, Oracle, MS SQL Server, or similar. Every town has experts that are well trained in SQL programming. Connecting the databases and installing data mining stored procedure to automate tasks is well within the realms even of smaller yards. Important here is that there is a consensus in all departments to make this happen. Bender Shipbuilding is well underway to achieve a company-wide integration of all departments.

Using an open and common database system, such as SQL server, allows each user to extend the capabilities of the database itself. Additional fields are easily added to any table that store additional information crucial to this user. Furthermore, any record in one database can be linked directly to any other record in a customer-defined database to extend on the capabilities.

Recent initiatives like Microsoft's .NET and Sun's Java Enterprise software architectures, along with the growing adoption of emergent technologies like XML and digital signatures for information exchange, should further enhance the ability of multiple vendor's tools to effectively and efficiently collaborate within the framework of a distributed and open product modeling system.

CASE STUDIES

Two particular recent case studies from shipyards using this sort of linked product model involve:

- A minimum integration for the production of a SPAR offshore structure in a newly built offshore yard on Batam Island in Indonesia, near Singapore.
- Bender Shipbuilding and the almost complete integration of the product model to all major departments company-wide.

MCDERMOTT ASIA, BATAM

The Batam yard of McDermott is a purpose-built yard with very little investment (Indonesia is not stable). Starting with a small number of top-level engineers from countries such as the UK and the US, all lower levels of engineering and drafting are filled by local staff with little beyond basic education. However, AutoCAD and general MS Office application skills are there.

Early on, ten days of ShipConstructor training took place for six local Indonesian drafters that would carry out all product modeling. All modeling was carried out on middle of the line computers. The product modeling team consisted of three designers/drafters, a nesting operator, and an NC-coder. Over a period of 12 months this small team was able to create a product model consisting of more than 60,000 parts comprising more than 12,000 tonnes of steel.

In the next step a simple procedure was developed to connect the ShipConstructor database to the database of ERP system Primavera P3E. Using the BuildStrategy assignments for every build stage from ShipConstructor the Bentley Enterprise Navigator was used to visualize every build step.

The political situation in Indonesia makes it very risky to invest in a lot of hard to move equipment. The yards facilities are for this reason kept at a minimum. For this reason the yard only has one heavy crane. Requirements for extra cranes was carefully planned and timed using group technology and resource matrix tools and cranes would be brought in just in time from nearby Singapore.

BENDER SHIPBUILDING

Bender Shipbuilding quite possibly has the most sophisticated product modeling and planning environment to be found in any shipyard worldwide.

In 1997 Bender was the first company to fully embrace 3D CAD modeling with a simple MS Access database. Bender quickly moved from the traditional 'stick-building' method commonly used by many yards on the Gulf of Mexico to a 3D modeling, with pipe penetrations pre-cut and automatically generated 3D assembly drawings. Furthermore, work packages would be created that group similar tasks, for example for profile cutting. Using this initial approach Bender reported a 50% savings of man-hours for unit assembly.

Since the introduction of ShipConstructor's SQL server database, Bender has consistently developed methods and procedures to connect and mine the information stored in it to other databases within the company environment. Most notably among these are the MIDAPS and WinShip developments.

The ShipConstructor product model with the SQL server database takes the central position in this system.

Bender has implemented a system in which each part name follows a specific model that identifies the part type and related processes. Additionally, stored procedures have been developed that run every morning to create all production activities for all newly created parts and assemblies during the previous 24 hours. This method replaces the work of five or six planners with one planner and a five-minute computing run every morning. Every new purchase item in the model is automatically identified and reported to the purchasing system. This is a dynamic process that does not have to wait until all work on a special unit has been finished. This provides enough lead-time for purchasing to order most parts just when they are needed, cutting down drastically on inventory storage requirements and capital cost.

LIFE CYCLE SUPPORT

A ship almost certainly costs much more to maintain through its lifecycle than it does to build. Anyone who has to deal with an existing fleet knows the frustration associated with inadequate initial design information, the maintenance of drawings, shipchecks of existing vessels and as-builts that aren't. Bills of material are always organized the way the shipyard needs to procure the parts, not the way a maintainer needs to get them, especially when the maintainer is handling multiple classes of vessels. The new drive to consider disposal also makes the model useful. The model by its nature contains an inventory of any materials which might be hazardous (now or later) and the amount, location, and purpose.

If the product model is available to the maintainer, he can use the model and the database to maintain configuration control throughout the life of the vessel and the databases can be interrogated, sifted and sorted as required. A shipboard engineer can interrogate a drawing developed from the database by clicking on a component and get the linked information needed to obtain parts or even to go to a manual. The derived drawings can also be used for emergency response.

Nelson (1998)[9] has shown how 2D DWF file (a compact vectorized file format developed by Autodesk for Web display) developed from the product model can be incorporated into a Web page and populated with hot links that link to any other type of Web-capable file. This is simple Web page development technology that a fair number of junior high school students are conversant with, so it is relatively accessible, and DWF viewers are available free that plug into standard Web browsers. Nelson produced damage control plates that link off to emergency procedure instructions, photos of a space (with labels) and other DWF drawings, which in turn can have other links. These plates can be used for emergencies (since they would reside on a laptop) or for training. Though such drawings can be developed from other sources, it is much easier to develop consistent drawings, especially considering the necessary interlinked structure, from the product model - they are developed in the same way work package instructions are. (Using the product model also ensures they are right – incorrect damage control data might be a problem in emergencies.)

In the long term, the need for an open database becomes even more acute. Young (1999)[13] has noted that product models are useless to maintainers who might not have the funds to buy a piece of software specialized for a given proprietary database format, or the trained personnel to use it. Product models must use at least "de facto" industry standards, and the vendors should provide proxies and similar features to allow the model to be used and maintained subsequent to ship delivery.

VIRTUAL REALITY

The next step is virtual reality models. Virtual reality models are also generated directly from the 3D product model and the conversion takes from a few seconds to a few minutes. After this, free viewers may be used by any person without any technical experience or specialized CAD computer experience to view these models. (These are essentially computer gaming techniques and tools.) Designers and drafters use CAD-built-in modules to perform instant 3D inspection of access and collision issues, while sales staff can use these models to educate potential customers about the various option of a particular vessel design. Engineering can use the same models to view the modeling progress and even provide daily updates over the web to the customers.

Using a virtual reality software, such as Navisworks, provides the further option to add links to any part within the model. These links can lead to documents, such as for maintenance, security and more just as the 2D DWF files discussed above, but the richness of the virtual environment enhances comprehension, thereby improving training and correct response in an emergency.

SCHLUMBERGER – VIRTUAL REALITY

Schlumberger operates several well-revitalization barges in the Gulf of Mexico. The barge top is occupied by a large amount of process piping in order to inject agents to revitalize wells with dropping production rates. Schlumberger is currently modeling several of these barges for training purposes.

Pipes and other process equipment is often hidden behind walls and under decks. Explaining the happenings to the operating crew can be quite a challenge without a visual verification. Using the virtual reality approach this becomes an easy task.

CONCLUSION

The authors have developed and used a variety of level of product models for marine projects and have found that an open system can be readily extended to provide a wide range of benefits in productivity increase, training and life cycle support. Though an open system might be less expensive, and easier to implement in terms of trained personnel than a proprietary closed system, the chief advantage is that open systems, using industry "de facto" standards is extensible well beyond the initial builders specifications.

This also implies that more thought and innovation is required on the part of shipyards developing these systems – they definitely are "roll your own". This can be both a liability and an opportunity, and the authors would like to suggest it is more opportunity.

The authors also have proposed a variety of techniques to use the database, and make two observations; first, the range of applications is limited only by imagination and need, so readers will be sure to come up with more ideas once they start thinking about it; second, many of the applications are linked and enable and cross-fertilize each other.

Finally, though the authors have given examples using particular products, the key concept we see is to use open, rather than proprietary products and systems to allow ongoing extension and improvement.

REFERENCES

2) Bell, V., "Death, taxes and the skilled labor shortage", (2003) *The Fabricator*, Fabricators & Manufacturers Association, Intl., Rockford, IL

3) Hammer, M., and Champy, J., (1993) *Reengineering The Corporation; A Manifesto For Business Revolution* HarperBusiness, HarperCollins, New York, NY

4) Harmon, R., and Peterson, L., (1990) *Reinventing The Factory; Productivity Breakthroughs in Manufacturing Today*, The Free Press, Simon & Schuster, New York, NY

5) Jolley, E. "AUTOTOOL/DB; A Solution for Ship Design", *CADalyst*, Jan 1992

6) Kosko, B., *Neural Networks and Fuzzy Systems: A Dynamical Systems Approach to Machine Intelligence,* 1999, Prentice Hall, Englewood Cliffs, NJ

7) Mahoney, R., (1997) *High-Mix Low Volume Manufacturing*, Hewlett-Packard Professional Books, Prentis Hall, Upper Saddle River, NJ

8) Mercier, L. Byington, T., Senkwic, W., and Barry, C. "Implementation of Integrated CAD/CAM Systems in Small and Medium Sized Shipyards, A Case Study" *Ship Production Symposium*, 1997, New Orleans, Society of Naval Architects and Marine Engineers, Jersey City, NJ

9) Nelson, A., Personal Correspondence

10) Ohno, T. *Toyota Production System* Diamond Publishing Company, 1978

11) Suzaki, K., (1987) *The New Manufacturing Challenge, Techniques for Continuous Improvement,* The Free Press, Simon & Schuster, New York, NY

12) Turner, J., Wharton, R., and Barry, C., "Group Technology Through "People Modules": A Case History" *Ship Production Symposium*, 2002, Boston, Society of Naval Architects and Marine Engineers, Jersey City, NJ

13) Young, Ryan, Comments to Oetter, *et al*, "Keys to CAD/CAM in Small Shipyards" *Transactions of SNAME*, 1998, Society of Naval Architects and Marine Engineers, Jersey City, NJ

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