VIRTUAL MANUFACTURING FOR SHIPBUILDING IN A GLOBALLY COLLABORATIVE ENVIRONMENT

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Introduction

The list of ship building related companies that are currently using some form of Virtual Manufacturing technologies includes: Avondale, Fincantieri, General Dynamics - Electric Boat, General Dynamics - Bath Iron Works, George Sharpe, John J. McMullen Associates, Newport News Shipbuilding, M. Rosenblatt & Son, Inc. Companies such as these have customers throughout the world that continue to demand increased quality, improved performance, shorter purchasing lead times and lower costs for their highly sophisticated and extremely complex products. Our customers are also interested in ways to make our products easier to use, even more reliable and maximize the time of operation before servicing. The key to successful business is to provide the customer what he/she wants, in a timely manner, any where in the world, at the lowest possible price. We believe that Virtual Manufacturing Technology can help your company become much better equipped to respond to your customers needs.

Virtual Manufacturing is being aggressively implemented across key industries including Aerospace, Automotive, DoD, DOE, Nuclear, R&D, and other industries to become more competitive, shorten launch cycles, and improve communications across global enterprises. Companies that have adopted Virtual Manufacturing technologies for the launch of new products and streamlining of operations include General Dynamics, General Motors Corp., McDonnell Douglas, Lockheed-Martin, Caterpillar, Northrop-Grumman, United Technologies and many other industry leaders. Time to market is being reduced up to 50 percent and lifecycle cost savings of 30 percent are being realized through implementation of Virtual Manufacturing technologies. Seventy to 80 percent of the tooling re-engineering and rework dollars have been saved by building the fixtures right the first time.

Virtual Manufacturing

In this paper, our definition for Virtual Manufacturing (VM) is: **An integrated set of tools** that provide us with the ability to model products, processes, and factories in an efficient and effective manner. VM tools serve as an effective interface with our customers and partners when determining and verifying the product usability, serviceability and functionality all in the virtual environment before any components are built. These tools will be used to help us make effective decisions (as we conceptualize and develop new products) by showing the impact of design parameters on the ability to produce the product in a timely and cost effective manner. The product design modeling information will be used as a basis for the development of the appropriate manufacturing processes and new equipment if necessary. The process and equipment models will then be used to determine the factory production capability requirements to quickly determine an accurate production cycle time and cost. VM tools will help in the decision making process when it comes to issues such as: “make vs. buy” of the components, where to build them, how much will it cost, can it be built, what is the most cost effective production process, and how fast can it be provided to the customer? The same models will be used to develop maintenance procedures and serve as an integral part of the required product utilization and maintenance training tools. Avi, tiff, vrml and vrml2 formatted data files are easily
created for inclusion in product user manuals, manufacturing process plans, and product maintenance manuals. This information is easily made accessible to the end user via CDROM or Web based formats. The same product data definition data will then be used to determine the factory production requirements and can be integrated into virtual factory models to determine the most effective equipment layout and to quickly identify the costs associated to produce the product within this facility. A single database of product/part information minimizes the potential for an engineer or process planner to develop design modifications or process plans based on outdated versions of information. The ultimate goal of successful VM users is to eliminate the need for engineering change orders from ever occurring because the product functionality, processing, maintaining and manufacturing concepts were successfully demonstrated and evaluated in the virtual environment before implementation. In a global business environment VM can dramatically enhance ones ability to communicate by transcending potential language barriers.

Virtual Prototypes

In the past, new products were conceptualized by design engineers and then scaled physical mock-ups were fabricated to determine the fit-up of components. It was not uncommon for unusable parts to be produced due to an oversight or miscommunication during the design process resulting in lost time and the generation of scrap. In good situations the parts may only have required additional machining, filing or shimming to allow for assembly. This iterative process could take weeks or years on very complicated products such as ships. Virtual Prototypes (VP) created during Virtual Collaborative Engineering (VCE) sessions clearly convey to the customer the functionality of the product. The same prototypes also show the manufacturing staff what needs to be produced.

Deneb Robotics, Inc.'s ENVISION® software provides the user with the following capabilities which makes it ideal as a tool for Virtual Prototyping:

- fast, interactive 3D graphics
- integral, complete 3D CAD system
- configurable color graphs that display cycle information
- CAD data translators including IGES, Pro/ENGINEER, Unigraphics, DXF, Intergraph, CATIA and VDA
- dynamic viewpoint manipulation, with multiple viewpoints that may be independently controlled and the ability to attach a camera to any moving or stationary part
- realistic lighting models that provide the ability to display shadows, colored lights, and part material surface highlighting
- advanced file management system featuring a Visual File Interface enabling files to be selected by either clicking on an image with the mouse or typing the file name
- a real-time system for collision, near miss, and minimum distance checks

For a company that deals in a global business environment we believe that this type of physics based virtual modeling technology truly enhances ones ability to communicate and to transcend potential
language barriers, because it is much easier for the human brain to absorb visual data rather than verbal or paper documentation regardless of your native language.

General Dynamics Electric Boat Division are currently designing, evaluating, and optimizing new submarines utilizing this VP approach. Operating under a contract from the Advanced Research Project Agency's (ARPA) Marine Systems Division, Electric Boat demonstrated the feasibility of state-of-the-art simulation-based design (SBD). The objective was to implement an accurate, efficient, and dynamic environment for design, rapid prototyping, concurrent product and process development, mission planning, operation maintenance, and training. Traditional prototyping methods can take several months to physically build and test, and at a great expense. As part of this program a demonstration model was created to evaluate a proposed torpedo loading mechanical system as shown in Figure 1. The geometry files were imported from the Computer Aided Design software into the

Envision VP modeling environment in the assembled condition. Within Envision, EB engineers were able to define the range of motion of the moving parts as well as the acceleration and velocities at which they were to move. The torpedo loading sequence was developed using Envision through a Graphical Simulation Language (GSL) to create a simulation of the process. Upon exercising the simulation, the collision detection capabilities of Envision captured a potential design flaw (Figure 2) which would have prevented the ability to use this mechanism as designed. The VP model was used to identify the colliding parts quite easily by highlighting them in red. Collision such as these will occur either because the functional sequence order was defined incorrectly or because there was not enough clearance designed in the system for the parts to move the necessary amounts. In this case, we saw that it was a spatial limitation. The parts were sent back to the Envision CAD world in the colliding positions, so that engineers could easily see the problem, and redesign one of the bulkhead structures, and thus eliminate the problem. This could all be done in a matter of a few hours as opposed to how much time and energy it would have required if it had been implemented on the real ship. The same model could conceivably be used to generate the process sequence programs for the controlling computer, and to verify that real control system sequence functioned correctly by connecting the model to the controller using digital/analog interface board. Other projects conducted in this program demonstrating the power of the Virtual Prototype included:
- A demonstration of the use of Envision to show the impact of various hull designs on the ship performance in a virtual sea based on the output of internally developed computer programs (Figure 3).
- The loading of a cargo ship at dock (Figure 4).
- The loading of a hover craft into the mother ship as they both floated on various sea state levels.
- The introduction of human modeling elements to validate the engine startup procedure. By mounting camera on the human model's eye it is possible to validate site lines within the ship's various compartments.
- A simulation of the process of fire fighting on board a ship utilizing state-of-the-art immersion goggles and human motion tracking technology.

![Figure 3](image.png)

![Figure 4](image.png)

EB personnel generally feel that by simulating kinematic, dynamic and mechanical characteristics of a model submarine, its components and subsystems, engineers create a multidisciplinary environment which to evaluate a wide range of parameters and optimize the design based on the results. Subsequent to the ARPA demonstration project, Electric Boat has adapted the SBD approach to design and now utilizes 26 seats of ENVISION VP software from Deneb Robotics, Inc. Envision fly-through design review sessions are conducted almost daily.

Assembly Sequence Development

The end result of a typical CAD designing effort is the product and part geometry in the final assembled condition. It up to the manufacturing process planners to figure out how the pieces will get together and how they will be made. The Virtual Prototype can be of great value to this process as well. The Deneb Assembly option for Envision VP provides the user with the ability to very quickly pull the various parts and subassemblies out of the final assembly state (using the collision and clearance detection capability to validate that the parts can indeed be removed through the space provided) via a dragging and dropping process with the mouse. During this process, a Gant chart is documenting the sequence. The Gant chart can be edited by cutting and pasting to change the order of disassembly, if necessary. The Gant chart can be exported into an ASCII text file for inclusion in the manufacturing process plans. Once the parts have been disassembled successfully, with a single mouse click, the sequence can be reversed, thereby generating the assembly sequence. The swept volume capability provided within Envision provides the user with the ability to create 3D geometry files that can be used to represent reserved space in the final design so that it will be possible for parts...
removal in a maintenance operation. Once the assembly sequence is verified to be correct, tiff images, avi recordings, vrml and vrml2 files can be generated for documentation of the assembly process as well as the disassembly and re-assembly for maintenance processes. The use of Deneb/ASSEMBLY provides many benefits including improved communication, improved quality, reduced costs, and reduced time to market.

Virtual Process Models

Ergonomic Task Development

Deneb/ERGO option enables the user to rapidly prototype human motion within a workplace, then perform ergonomic analysis on the designed job(s). As mentioned above, this might be done when developing how to use a product, or maintain a product as well as how to build the product and its parts. The following functions and tools provide the ability to accomplish these tasks:

- a dedicated human motion programming interface that includes inverse kinematics and graphical programming for the human models
- 5, 50 and 95 percentile male and female models
- an energy expenditure prediction model
- guidelines for two-handed lifting
- a posture analysis system
- a work-measurement standard to estimate time standards for jobs

The features from ENVISION and Deneb/ERGO combine to give the user a versatile, flexible, and powerful tool for human factors engineering. In addition to studying the human element in the environment, Deneb/ERGO allows human models to interact with other moving entities like robots and conveyors. Figures 5 and 6 show some examples of some ergonomic models.

Figure 5

The human model functional activity is developed by the generation of poses that are recorded in the correct sequence for the operation. Graphical interfaces are created to help with this task by providing the user with an intuitively easy to understand format. For example when in the teaching mode, the first action for the human model might be to walk over to a table and grab an object. This
is done by reaching the position at the table, and the software automatically generates the walking motion to that spot. Simple selections for reaching and grabbing the part are done via mouse clicks and then stored. Other poses such as sitting, stooping, kneeling and squatting are all generated with a couple of mouse clicks. Once the sequence of the operation has been completed within the model, the analysis of the process can then be performed. The output of this analysis will be information like the energy expended during the process, RULA (Rapid Upper Limb Assessment) assessment of the motion performed, NIOSH (National Institute of Occupational Safety and Health) lifting guidelines based on the identified mass of the objects being manipulated, and the time required to perform the task via the use of MTM-UAS (Methods Time Measurement - Universal Analyzing System).

Robotic Workcell Development

Fincantieri Shipyards S.p.A, Monfalcone, Italy, specializes in cruise and merchant ship construction. Welding stations at the Monfalcone shipyard include large multi-axis gantry systems provided by Motoman and IGM. The gantry systems support either two or four robots during the welding of large ship sections. The traditional welding method typically required 50 to 100 man-hours of on-line programming per one hour of robot cycle time. Therefore, a weldment requiring one hour of welding needed up to two man-weeks to program. As programming was done on-line, the robot was out of production the entire time. Shipbuilding is plagued with small weld batches as no two ships are identical nor are any two ship sections. Each section requires a unique program. In addition, the robot requires eight hours, or more, to weld one ship section. Skilled robot programmers, using the teach pendant pendant mode of programming, often takes as much as one month of programming time (two shifts per day) to complete each of the more than 100 sections in a typical ship.

A virtual environment from Deneb Robotics, Inc. known as the Interactive Graphical Programming (IGRP) provides the user with the ability to test out multiple styles and brands of robots, as well as how the robots might be integrated with a gantry style auxiliary axis positioning system. Figure 7 and 8 shows a close up of two different robotic welding workcell models that are used for the fabrication of structural sections. In this type of operation that consists of multiple

![Figure 7](image1)

![Figure 8](image2)

identical welding patterns being performed in a matrix like array, it is possible to install the robots in a master/slave (one robot leads, and the others follow the same process sequence) arrangement to increase the speed of the process. The workcells shown here were modeled with IGRP with an optional software module called the Arc Welding Macro Programming system (AMP). The AMP
system was developed jointly by a team of Deneb software engineers and Fincantieri process
engineers, technicians, and operators to define the software requirements. It was designed to provide
an easy to use arc-welding robot programming system for welders, not computer or robotic experts. It
is within the AMP system that welding processing parameters are stored for typical types of welds.
These are automatically set during the robot programming process by selecting the type of weld prior
to generation of the robot motion sequence.

By developing IGRIP workcell models during the conceptualization phase of the purchase of
the robotic arc-welding stations, Fincantieri was able to verify that the actual system would be able to
gain access to all the necessary areas of the ship components. The actual programming of the robots
was initialized before the real system was installed in the Monfalcone shipyard. Fincantieri now
achieves 100 percent off-line programming. No touchups are needed and all robot process data is
downloaded, including weld parameters, enabling the robot to maintain constant production. This is
the critical benefit of off-line programming.

These same workcell-modeling tools are being used very successfully in aerospace, automotive
and other commercial industries as well. Other specialized option packages are available for painting,
finishing (deburring), spotwelding and telerobotics.

CNC Controlled Machine Modeling

Virtual machine models can be created to show the entire machine functionality during the
removal of material in a machining operation. The generation of the NC code is done through the
existing CAD/CAM system. This type of model is very easy to use to verify the functionality of a NC
program prior to downloading it to the actual machine. The models can provide information on the
processing times, collision detection and the efficiency of the program for processing materials.
Deneb Robotics, Inc.'s Virtual NC modeling software is capable of identifying machining conditions,
which have, been proven to cause chatter, reduce scrap through the detection of undercuts and gouges,
and detect conditions which contribute to tool breakage. Traditionally, machining cycles waste up to
30 percent to 40 percent of the cycle time. This wasted time can be attributed to the use of slower feed
motion when a rapid motion is acceptable, performing unnecessary motion, excessive motion, and/or requesting repetitive tool
changes.

Lockheed Martin Energy Systems, Inc. (Energy Systems), Oakridge Y-12 Plant, TN,
successfully modeled an 8-axis Giddings & Lewis eight inch boring mill with CNC control
as part of a federally funded project for manufacturing process development for the
Navy's Seawolf submarine program. The
machine model (Figure 9) was created and
validated by a team of Lockheed Martin and
G&L engineers as part of the system design
process. The model was used to develop the post-processor and probing routines for the machine
before it was completely fabricated. While the machine was still being fabricated a team of nine NC
programmers were developing and validating the NC codes that would be used to machine the parts
required in this program. Using Deneb/Virtual NC, they significantly reduced setup time and began
part production as soon as the equipment installation at the manufacturing site was complete. Tooling
and fixture setups were also verified and readied for production during this time. Because simulation
allowed these steps to be done in advance, actual part production could begin the day the machine was
turned over to the production shop.

During the simulation of a particularly complex flat-end mill operation, for example, the
software indicated a collision. It was not at the tool/workpiece interface but at a point about 40 inches
from the tool and outside the operator’s field of vision. The manufacturing engineer solved this
problem by extending the tool an additional two inches, and sent the data back through the post-
processor to create a new program. When the new program was simulated, the software detected no
collisions. Prior to machining the part, the machine operator was called to watch the simulation so he
would be prepared for the closeness of the clearances. Virtual NC automatically identifies the
conditions in the cycle when a feed move has been programmed, but no cutting actually occurs. This
information can be used to restructure the NC program to reduce this wasted cycle time.

Energy Systems’ experience showed that use of Deneb/Virtual NC for machine tool and
machine process simulation dramatically reduces costs by preventing crashes that can disable the
machine and delay the completion of the project. Simulation also reduced hidden costs by optimizing
machining processes, improving the effectiveness of operators and engineers, and improving process
capability. One of the most significant benefits of Deneb/Virtual NC on this project is that 500, 8-
axis NC programs have been used on the machine without a single crash. This program dramatically
should how the virtual modeling provided a means to eliminate the risk of mechanical damage to the
machine tool, workpiece, fixtureing, and tooling. They were able to develop and debug the post
processors with greater ease and ahead of time. The models were also used to train both NC
programmers and the machine operators before the machine was installed, and as an offline training
tool while the machine was producing parts.

**Virtual Factory Modeling**

In the past traditional factory modeling tools have been used throughout industry to determine
how many machines were needed to provide some target production level. Once the answers were
provided, the modeling effort stopped. Early factory modeling tools were cumbersome to use and the
accuracy was often suspect because the results were numerical tables which needed to be interpreted
by skilled professionals. Due to the visual nature of Virtual Factory (VF) modeling tools, it is now

![Figure 10](image1)

![Figure 11](image2)
much easier to convince a customer that the model truly represents the facility functionality. Figures 10 and 11 show views of a Virtual Factory model generated by United Technologies Research Center personnel of a proposed composites fabrication facility for the High Speed Civil Transport Program. It is also much easier to conduct "what if" scenario analysis because the changes are very clearly seen and understood. VF models clearly provide the users with an:

- Improved understanding of factory functionality
- Identification and quantification of throughput bottle-necks, WIP, equipment/labor utilization, impact of downtime and maintenance
- More accurate estimates of production costs
- Continuous improvement "What If..." analysis
- Evaluation of alternative scheduling approaches

VF models provide the user with integrated graphical presentation capabilities such as real time strip charts, pie and bar charts as well as object color changes to indicate resource status. Model summary reports quickly identify the material flow bottlenecks.

Many companies throughout the world are adopting the principles of Just in Time (JIT) and "Kaizen" (Continuous Improvement). Entire manufacturing facilities are being evaluated and re-organized to minimize the occupied real estate area, minimize part distance traveled, and minimize the product production cycle. VF models have been successfully used to enhance this process. An "as-is" VF model of an existing facility is used to track and show how the material flowed between resources. Spread sheet data files are used to input information for the part routing through the facility, as well as processing times, setup times, teardown times, labor, tooling and fixturing requirements. The distances parts travel and the time in the facility for the parts are automatically recorded and saved in a spread sheet format. By sorting and analyzing this spread sheet information it becomes clear which pieces of equipment need to be moved to minimize the distances the parts will travel. This is done in an interactive, iterative manner to determine a more efficient facility layout. Total part travel distances can be reduced by over 50% based on the implementation of equipment arrangement determined by this "Kaizen on the Computer" activity. Virtual Factory modeling tools dramatically enhance the ability to understand a facilities functionality and serve as a means for continuous improvement in an organized and efficient manner. They should be used as "living" documentation of the facility functionality.

For the ship building industry the scenarios described above still apply for the land-based manufacturing facilities that create the components of the ship that are assemble at the ship yard. VF models could also be used to evaluate the functionality of the crew utilization, onboard shop functionality, chow line flow, and cargo loading and unloading. These models could also be used to evaluate the flow of ships through the yard to determine the quantities of dry docks and wet docks. Because these tools are physics based in nature, it is possible and necessary to create the models dimensionally.
accurate. Distances that ships, parts, and people need to travel obviously determine the amount of time it takes for material to flow between locations. Figure 12 shows a sample model of the flight deck on an aircraft carrier, and Figure 13 shows a sample of a model of a shipyard.

![Image](image13)

**Figure 13**

**Virtual Manufacturing Benefits**

Besides improved communications across multi-disciplinary product teams, specific benefits demonstrated and projected for key industries include:

- 50 percent reduction in time to market based on the increased speed of decision making and the parallel development of product and process designs
- $1-5 billion life cycle cost savings for new Navy/Air Force Aircraft development and production
- Achieve learning curve of third ship set on first ship set for new shipbuilding program
- Integration of global customers, subcontractors, suppliers and users early in the design and development cycle
- 25 percent reduction in the cost of new products due to the utilization of the Design for Assembly and Design for Manufacturing capabilities
- 70-80 percent reduction in rework costs for tooling and fixtures since they were proven out in the Virtual Manufacturing environment before initial fabrication

**Conclusions**

Virtual Manufacturing is being aggressively implemented across key industries including Aerospace, Automotive, DoD, DOE, Nuclear, R&D, and other industries to become more competitive, shorten launch cycles, and improve communications across global enterprises. Companies that have adopted Virtual Manufacturing technologies for the launch of new products and streamlining of operations include General Dynamics, General Motors Corp., McDonnell Douglas, Lockheed-Martin.
Caterpillar, Northrop-Grumman, United Technologies and many other industry leaders. Time to market is being reduced up to 50 percent and lifecycle cost savings of 30 percent are being realized through implementation of Virtual Manufacturing technologies. Seventy to 80 percent of the tooling re-engineering and rework dollars have been saved by building the fixtures right the first time.

In the not too distant future we believe that the VM tools described above will provide us with an easy to use system for enhanced global communication. It will become common place for design engineering teams and their customers to communicate together while being simultaneously immersed in the same virtual environment without leaving their office. Vendors and equipment suppliers will provide virtual models of their equipment for NC creation, verification and training tools, as part of their deliverable package. We will be able to provide factory tours to people, showing them their components being manufactured without them leaving their office. Virtual Factory Models will become "living" documentation of a facilities functionality by the direct connection to the real facility resources for on-line data collection, tracking of equipment, material and labor status.

We believe that VM Technology enhances our ability to communicate product functionality, new concepts for component fabrication and verification of the factory functionality required to produce these products. The visual nature of VM provides us with the ability to transcend potential language barriers in a global business environment.

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PRACTICAL APPLICATION OF COMPUTER SIMULATION MODELING FOR ANALYSIS OF SHIPYARD PRODUCTION PROCESSES

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Introduction

In an effort to build cost competitive ships for the world market, many shipyards are investigating building methods and equipment that will streamline production and reduce vessel construction times. With simple production process systems, this investigation is a fairly straightforward process. The existing “As-Is” production process is thoroughly analyzed through the use of flowcharts and performance statistics, then compared to a “To-Be” process incorporating new techniques and equipment. If the “To-Be” process achieves the objectives of management with a justified return on investment, the new process is implemented.

The construction of a ship consists of thousands of interactions between products, processes, and resources. All three entities have an effect on each other and a small change to one can cause a large change in the overall operation of the system. Many of the techniques utilized to analyze smaller systems become very labor intensive when manually analyzing ship production processes. Assumptions are used to break the process down into manageable pieces to be studied by a process improvement team. In some cases, the necessity of making these assumptions can cause problems by oversimplifying the process. The same details that make the system difficult to analyze are the details that contribute to the overall inefficiency of the process. Advances in personal computer processing speed and the development of user-friendly simulation software, however, now provide shipyards with an effective tool in performing investigations of difficult to analyze processes.

National Steel and Shipbuilding Company (NASSCO) in San Diego, California has been using computer simulation to make these difficult to analyze processes more manageable. The manufacturing simulation software, ProModel, was used as part of a process improvement initiative to reduce the cycle time of the yard’s Panel Line to 4 hrs/panel. The variation of the work content in panels built on the line and the interaction between workstations made this a formidable task. Through the combined efforts of the team members, valuable insight into the everyday operation of the line was gained. This paper highlights the steps taken by the Process Analysis Team to analyze the Panel Line, NASSCO’s use of computer simulation software in this initiative, as well as, the results of the analysis.

Description of NASSCO’s Panel Line

The layout of NASSCO’s panel line is shown in Figure 1. The Panel Line consists of nine process specific stations. Plates enter the line at Station 1 where they are fit and tack welded together. The fitting and welding of deck sockets also begins in this station. The ships currently being built at

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NASSCO are Roll-On/Roll-Off ships for the Military Sealift Command. In order to facilitate the lashing of cargo, thousands of cloverleaf-shaped holes are cut into the deck of the ship.

**Figure 1. Layout of NASSCO’s Panel Line**

Bowls are welded to the underside of the deck to prevent water from flowing through the holes. These bowls are referred to as “deck sockets.” Deck socket welding continues as the panel moves by conveyor into Station 2. For the majority of the panels built on the line, the deck socket welding is completed in this station.

In Station 2 the plates are welded together with a semi-automatic one-sided welder. If any weld repairs are needed they are done in a pit between Station 2 and 3. The welded panel is then moved into Station 3 where layout of the longitudinals and transverse deck beams is done. The perimeter of the panel is burnished to create a square panel. Longitudinals are manually fit in Station 4 and welded in Station 5. A semi-automatic welder is used in Station 5 to do the welding of the stiffeners. The welder is capable of welding both sides of four stiffeners simultaneously. After the stiffeners are welded, the panel moves into Station 6 for the fitting of transverse deck beams (webs). The welding of the webs and any additional small parts is done manually in Stations 7 and 8. Finally, the completed panel is moved into Station 9 where the inspection is done. If any additional welding needs to be completed on the panel it is also performed here before the panel is lifted off the line by a gantry crane and moved to the next process location.

Panels are moved into the next station as soon as possible and removed from the line when complete to make room for new panels. Removal of the panels is done in four locations including the end of the line. Blanket plates (panels without longs and webs) are removed after the one-sided-welder in Station 2. Panels that only require longitudinals are removed at Station 5. In some cases, the weldout of the webs is completed in the first weldout station (Station 7). When this occurs, the panel is immediately removed from this station.

**Initiative to Implement the 4hr Line**

NASSCO’s objective in reducing the cycle time of the Panel Line was to increase throughput and efficiency. By implementing a line that consistently indexes every 4 hours, it would also be easier to schedule starts and lift-offs. On average, a crane could arrive at the beginning, middle and end of every shift to remove a panel from the line. A process improvement team was formed consisting of a cross-section of the Panel Line’s process stakeholders. The team’s task was to recommend the changes to the process that would be necessary to reduce the line’s cycle time to 4 hrs/panel. Cycle time for the line was defined as the elapsed time between finished panels. The team worked on reducing the cycle
time primarily through the elimination of non-value-added tasks and replacement of aging and inefficient equipment.

Process Analysis of the 4hr Line

The first operation of the Process Improvement Team was to flowchart the existing Panel Line process. Included in the flowchart was the average time and required manning for each task. Because of the complexity and scale of the Panel Line operation the 80/20 rule was used to determine which tasks should be included in the flowchart. If the task was performed on 80% of the panels built on the line, it was included in the flow. To further simplify the process a “standard” reference panel was created to represent the average work content of the panels run down the line. The work content of each panel was characterized by the number of plates, longitudinals (stiffeners), manufactured T’s (webs), and deck sockets used to build the panel. The components were averaged for an entire ship’s worth of panels to determine the number of parts in the reference panel. These averages were used by the Process Improvement Team for the reference panel and consisted of:

- 5 Plates (4 Seams) – Average 4.4
- 12 Longitudinal Stiffeners – Average 11.6
- 5 Transverse Manufactured T’s (Webs) – Average 4.8
- 120 Deck Sockets – Average 120

After flowcharting the existing process, the Process Improvement Team reviewed the tasks to determine which added to the inefficiency of the panel construction either by not contributing to the physical change of the product or because of the use of ineffective equipment. These tasks were eliminated to improve the efficiency of the process. The order of many tasks was changed to accomplish them in parallel rather than series, and some work was moved off the line to further reduce each station’s individual cycle time, thereby reducing the overall panel cycle time to 4 hours. The effects of these changes were quantified in terms of new times and manning and included in a flowchart of the “To-Be” process.

The times for each task on the “To-Be” flowchart were summed along the critical path to determine the individual station times. The station times for the “To-Be” Panel Line are shown in Table 1. One of the changes the Process Improvement Team made in the “To-Be” process was the timing of the panel movement on the line. Instead of moving a panel into the next station when it was completed, the entire line moved every four hours. This was done to simplify the manual analysis of the line. Since the whole line moved at the same time, each station had the same 4 hour average station span time (Avg Span). Span time was defined as the duration each panel occupies a station before being moved to the next one. The amount of time the panel was being worked on during its span time in the station was defined as the process time (Avg Process). The process times developed by the Process Improvement Team were obviously less than the 4 hour span time otherwise the average panel would have moved into the next station uncompleted. The maximum process time (Max Process) for the stations shown in Table 1 is equal to the average station process time since all of the panels are the same “standard” reference panel. The line span time (Average Line Span Time Per Panel) was defined
as the time the panel is on the line from start of assembly to finish. The one-sided welding station has the highest process time (236 min), and thus is the pacing station for the 4 hour line.

Table 1. Station Times for the “To-Be” Panel Line (Times in Minutes)

<table>
<thead>
<tr>
<th>Station</th>
<th>Avg Span</th>
<th>Avg Process</th>
<th>Max Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Plate Fitting</td>
<td>240</td>
<td>180</td>
<td>160</td>
</tr>
<tr>
<td>1 and 2-Deck Sockets</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>2-One-Sided Welding</td>
<td>240</td>
<td>230</td>
<td>230</td>
</tr>
<tr>
<td>3-Layouts/Per Burn</td>
<td>240</td>
<td>220</td>
<td>220</td>
</tr>
<tr>
<td>4-Stiffener Fitting</td>
<td>240</td>
<td>205</td>
<td>205</td>
</tr>
<tr>
<td>5-Stiffener Welding</td>
<td>240</td>
<td>210</td>
<td>210</td>
</tr>
<tr>
<td>6-Web Fitting</td>
<td>240</td>
<td>187</td>
<td>187</td>
</tr>
<tr>
<td>7-Weld Out 1</td>
<td>240</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>8-Weld Out 2</td>
<td>240</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>9-Inspection and Ship</td>
<td>240</td>
<td>121</td>
<td>121</td>
</tr>
</tbody>
</table>

Avg Panel Cycle Time 4.00 hrs (240 min)
Avg Line Span Time Per Panel 36.0 hrs

Computer Simulation Modeling of the 4hr Line

Although the process flow had been completed for the “standard” reference panel, there was a realization that the reference panel only represented a portion of all of the possible panel types built on the line. The effect of building different panel types that have varying work contents was unknown. It was decided that a computer simulation of the panel line was necessary to quantify the effect of building panels with variable work content on the “To-Be” Panel Line.

Development of the Panel Line Model

In order to quickly set up a model that would evaluate the “To-Be” process, the project team decided to enhance a Panel Line computer model originally developed for NASSCO by a local consultant, Kiran Consulting Group, for the purpose of investigating the use of robotics on the line. The project team needed to modify the computer model so it would be better suited for its new purpose of analyzing the “To-Be” Panel Line process. In Kiran’s model, a single reference panel, which was different than the Process Improvement Team’s reference panel, had a station time associated with it for each fitting and welding process that took place on the line. Some of these times such as the deck socket and web welding operations were dependent upon the number of people assigned to the task. The line, therefore, could be balanced by increasing or decreasing the manning for tasks that were creating bottlenecks in the line or had low resource utilization. Automation could also be substituted in place of manpower to determine the overall effect on the system. Manning and automation, however, were not the key issues in the “To-Be” Panel Line process. The model needed to be adapted to accept panels of different work contents rather than a single reference panel.

The first step in adapting the Panel Line model was to determine the level of detail necessary to accomplish the objectives of the task. When conducting a simulation project it is important to remember that the time and funding necessary to build the model is directly proportional to the detail.
of the model. As the detail of the model increases, so does the cost and effort necessary to build, debug, validate, and use it. Since the model's primary use was to determine the effects of building variable work content panels on the panel line rather than optimizing the line through process changes, design changes, and manning, it was decided that each individual task and required manning level did not have to be explicitly modeled. The fact that the model was to simulate the system variation due to work content and schedule, however, meant that it could not be modeled by merely inputting only the overall assembly times for each panel. The model had to be built in a fashion that captured both individual panel complexity and the effects of overall panel build sequence. These objectives were met by modeling the fitting and welding times on a per plate, long, and web basis to capture the variation in work content, and designing the model to accept a specific panel sequence.

**Modeling Process Times**

In order to develop the simulation model's assembly times for both reference and variable work content panels, the Process Improvement Team's reference panel and station times (shown in Table 1) were used to determine the process time per seam, deck socket, long, and web. For example, the Average Process time for the reference panel in Station 1 (180 minutes) was divided by the number of reference panel seams (4) to get the fitting time per seam at Station 1 (45 min/seam). This is the only time needed in order to capture the processing time for Station 1 when the identical reference panels are run through the model. When panels with variable work content are modeled, however, both the number of seams and the length of each seam will alter the total fitting time in the station. In order to represent this variation from panel to panel, the fitting time per seam was divided again by the number of reference panel webs (5) which run perpendicular to the seams to capture the effect of differing seam lengths. This resulted in a processing time per-unit for Station 1 of 9 min/seam/web. This same process was used to develop per-unit times for all nine stations on the line and captured the work content of both the reference and variable work content panels.

Additional time for tasks such as the setup of equipment, transportation of the panel, and clean up was not explicitly modeled, but included as part of the process time on a per plate, long, and web basis. Downtime was not included in the modeled processes for two reasons. First, it would take some time to analyze how it currently affects the process, understand how it would affect the "To-Be" process, and develop it into a form that could be utilized in the model. Second, it was not necessary to include it. Initially, to meet the basic objectives of the project. If the results of the model indicated that a 4 hour cycle time could not be achieved in a system without downtime, then the project team could safely conclude that it would be impossible to achieve the goals in a panel line process with downtime. There was no point in spending the time to include downtime until it was known if the "To-Be" process could meet its objectives without it.

**Modeling Process Flow**

Because the computer simulation model could control the movement of each panel into the next station as soon as possible, it was not necessary to constrain the line by forcing each panel to have the same station span time. As mentioned earlier, the entire line moved every four hours in the "To-Be" process done by the Process Improvement Team to simplify their analysis. This restrains the throughput when variable work content panels are built. Smaller panels with a work content less than 4 hours in duration will not move off the line as quickly as they would if they were allowed to move to
the next station when completed. Moving the panel as soon as possible, not only increases the throughput of low work content panels, but allows work to begin on the following panel earlier, creating a more efficient use of the line’s limited space. This is the main reason the current practice on the actual NASSCO panel line is to move each panel into the next station as soon as possible.

**Modeling Process Sequence**

The final change necessary to adapt the existing Panel Line model for this project was to program it to read in a schedule of reference or variable work content panels by means of a data file. This schedule, created by the Master Planning Department, included all of the panels built on the Panel Line in the sequence in which they were built. It also detailed the number of plates, deck sockets, longs, and webs on each panel. The information is read in and mapped to variables in ProModel where it is used to calculate the process times. The first plate of the first panel arrives in Station 1 at the start of the simulation and from that point, the process times drive the rate at which panels are completed. During the simulation, ProModel keeps track of performance statistics on location and resource usage, quantities of parts, and process times. This information can be reviewed at the end of the simulation in both tabular and graphical form.

**Results from Model for the Reference Panel**

Once the model was adapted to represent the Process Analysis Team’s “To-Be” process, it was run to validate that it produced the same performance. In order to do this, a schedule of 290 identical reference panels was created and entered into the input data file. This is the same number of variable work content panels that would be tested. The results of the reference panel model are shown in the “Simulation -Ref Panel” column in Table 2.

<table>
<thead>
<tr>
<th>Station</th>
<th>Process Analysis -Ref Panel</th>
<th>Simulation -Ref Panel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg Span</td>
<td>Avg Process</td>
</tr>
<tr>
<td>1: Face Fitting</td>
<td>240</td>
<td>180</td>
</tr>
<tr>
<td>1 and 2: Deck Sockets</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>2: One-Sided Welding</td>
<td>240</td>
<td>230</td>
</tr>
<tr>
<td>3: Layout Per Burn</td>
<td>240</td>
<td>220</td>
</tr>
<tr>
<td>4: Stiffener Fitting</td>
<td>240</td>
<td>203</td>
</tr>
<tr>
<td>5: Stiffener Welding</td>
<td>240</td>
<td>210</td>
</tr>
<tr>
<td>7: Weld Out 1</td>
<td>240</td>
<td>180</td>
</tr>
<tr>
<td>8: Weld Out 2</td>
<td>240</td>
<td>180</td>
</tr>
<tr>
<td>9: Inspection and Ship</td>
<td>240</td>
<td>121</td>
</tr>
<tr>
<td>Avg Panel Cycle Time</td>
<td>4.00 hrs (240 min)</td>
<td>3.39 hrs (203 min)</td>
</tr>
<tr>
<td>Avg Line Span Time</td>
<td>36.0 hrs</td>
<td>10.2 hrs</td>
</tr>
<tr>
<td>For Panel</td>
<td>36.0 hrs</td>
<td>10.2 hrs</td>
</tr>
</tbody>
</table>

The Average Span times of the model's reference panel are less than or equal to the span times of the Process Improvement Team’s reference panel. This is an effect of moving each panel as soon as possible into the next station. The Average Process times for both are equal with the exception of Station 7 and 8 Weld Out. This is the natural balance of the work in these two stations if panels are
moved into Station 8 when it becomes available in order to make room for additional panels on the line. The sum of the work done in both stations of the simulation model, however, is still equal to the 360 minutes of work done in Stations 7 and 8 of the "To-Be" Panel Line process. Because 290 identical panels were used in the reference panel simulation model, the Maximum Process times are equal to the Average Process times for all of the stations.

The six hour reduction in Average Line Span time per panel is a minor issue in the comparison of the times. Because the panels are able to move to the next station when they are finished, the panels spend less time on the line. The biggest advantage to this is that the first panel comes off the line 6 hours earlier in the model. This reduction in span time is important in the scheduling of panels for the line since there is a 6 hour reduction in time from start to finish, but it is not an issue in the performance of the line. The most important factor in judging the performance of the line is the Average Cycle time per panel. This is the rate at which finished panels will come off the line, and is equal for both the Process Improvement and Simulation results. Because of the close agreement between the times developed by the Process Improvement Team and simulation model, the project team felt that the model was validated and was a reasonable representation of the process. The next step was to load a schedule of panels consisting of variable work content into the model.

Results of the 4hr Line with Variable Work Content Panels

Two hundred ninety panels with variable work content were input into the model rather than the identical reference panels. A portion of the data file is shown in Table 3.

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Plates</th>
<th>Seams</th>
<th>Sockets</th>
<th>Stiffeners</th>
<th>Dart 4 Passes</th>
<th>Webs</th>
</tr>
</thead>
<tbody>
<tr>
<td>V168-5001</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>T167-S001</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>T168-A02</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>T223-S001</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>T125-S001</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

The results of the Variable Work Content Panel runs are shown in Table 4. The Average Cycle time per panel is 0.63 hours greater than that for the reference panel. This indicates that using the same processes developed for the reference panel will not result in a 4 hour cycle time for panels with variable work content. The 4.63 hours per panel is an optimistic view since downtime has not been included in the model. Any disruption in the normal operation of the line will drive the average cycle time even higher.

The Average Span time and Maximum Process times are higher for the panels with variable work content. The Average Process times are not equal to either the Average Span or Maximum Process times (since the panels had variable work contents) and most are lower than those for the reference panel. One would expect that a lower average process time would contribute to a lower panel cycle time. The larger Average Span times, therefore, must be the cause of the higher cycle time.

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Table 4. Comparison of the Times for Panels with Variable Work Content (Times in Minutes)

<table>
<thead>
<tr>
<th>Station</th>
<th>Process Analysis-Ref Panel</th>
<th>Simulation -Ref Panel</th>
<th>Simulation -Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Plate Fitting</td>
<td>240</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>1 and 2-Dock Sockets</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>2-One-Sided Welding</td>
<td>240</td>
<td>236</td>
<td>236</td>
</tr>
<tr>
<td>3-Layer/Per Burn</td>
<td>240</td>
<td>220</td>
<td>220</td>
</tr>
<tr>
<td>4-Stiffener Fitting</td>
<td>240</td>
<td>203</td>
<td>203</td>
</tr>
<tr>
<td>5-Stiffener Welding</td>
<td>240</td>
<td>218</td>
<td>218</td>
</tr>
<tr>
<td>6-Web Fitting</td>
<td>240</td>
<td>187</td>
<td>187</td>
</tr>
<tr>
<td>7-Weld Out 1</td>
<td>240</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>8-Weld Out 2</td>
<td>240</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>9-Inspection and Ship</td>
<td>240</td>
<td>121</td>
<td>121</td>
</tr>
</tbody>
</table>

Avg Panel Cycle Time: 4.00 hrs (240 min)  
Avg Line Span Time: 3.86 hrs (231.6 min)  
Per Panel: 36.9 hrs 24.2 hrs 35.3 hrs  
* Max Due to Startup/Shutdown State Max Known in Dockers

Causes of Higher Span Times In Variable Work Content Model

The higher span times are caused by blockages in the line. The Location States for the Reference Panel model are shown in Figure 2. The Location States for the Variable Work Content model are shown in Figure 3. These are the percentages of time that each location was in use (Operation), being setup for processing (Setup), not being used (Idle), waiting for resources to process a panel (Waiting), unable to move a completed panel into the next location (Blocked), or unable to process a panel due to planned or unplanned downtime (Down). The Figures show that the stations were either in operation, idle, or blocked during the simulation. Setup and downtime is not seen in the graphs since they were not explicitly modeled, and enough resources were used to prevent any wait time.

Figure 2. Location States for the Reference Panel

Single Capacity Location States

<table>
<thead>
<tr>
<th>Name</th>
<th>Setup</th>
<th>Idle</th>
<th>Waiting</th>
<th>Blocked</th>
<th>Down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sta2 Deck Sockets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta2 One-Sided Welding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta3 Manual Layout</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta4 Stiffener Fitting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta5 Stiffener Welding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta6 Web Fitting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta7 Weld Out 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta8 Weld Out 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta9 Inspect and Ship</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
With the exception of Station 2, 7, and 9 all of the locations in the Reference Panel model are in operation for a reasonable percentage of the time. There is very little idle time. Station 2, 7, and 9 have the lowest process times and therefore, are in operation less than the other locations in the balanced system.

Figure 3 shows a much lower utilization of the locations in the Variable Work Content model. The remainder of the time is spent with each station either idle or blocked. The blockage is created whenever a downstream panel prevents a completed panel upstream from moving into the next station. Figure 3 shows three major jumps in the amount of blockage in the line. Starting at the end of the line, the first occurs between Stations 6 and 7 where the blockage time increases from near zero to a little more than 5%. The second occurs between Stations 4 and 5, and the third between Sta2_Deck_Sockets and Sta2_One_Sided_Welding.

**Figure 3. Location States for the Variable Work Content Panel**

```
<table>
<thead>
<tr>
<th>Location</th>
<th>Setup</th>
<th>Idle</th>
<th>Waiting</th>
<th>Blocked</th>
<th>Down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sta2_Deck_Sockets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta2_One_Sided_Welding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta3_Manual_Layout</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta4_Stiffener_Fitting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta5_Stiffener_Welding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta6_Web_Fitting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta7_Web_Out_1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sta8_Weld_Out_2</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Sta9_Inspect_and_Ship</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

These three jumps correspond to the three major bottlenecks in the line:

- Station 2 One-Sided Welding
- Station 5 Stiffener Welding
- Station 7 and 8 Weldout

Station 8 is also considered to be a bottleneck due to the shared work and dynamics between itself and Station 7. When Station 8 becomes available, the panel in 7 is moved into 8 regardless of work content left on the panel. The next panel that moves into Station 7 is processed until it is completed (and then taken off the line) or Station 8 is again available. A possible scenario could exist whereby panels in Station 7 and 8 could be in process while the panel in Station 6 is complete. Station 7 in this case is not the bottleneck since it is ready to move when 8 becomes available. Until Station 8 is available, the panel continues to be processed. The blockage in Station 6, therefore, is due to the longer process time for the panel in 8.
Causes of Blockages

The blockage in Sta2_Desk_Sockets is primarily due to panels which have either no deck sockets or a number that can be completed in Station 1. If there is no work to be completed on the panel when it enters Sta2_Desk_Sockets it will want to continue on into Sta2_One_Sided_Welding. If a panel is in Sta2_One_Sided_Welding, this move cannot take place resulting in blockage time. Since Sta2_Desk_Sockets acts as a buffer station, this blockage is not necessarily a problem for the line. Understanding that the blockage exists, however, does present the opportunity for increasing the throughput of the line. By reducing the Average Span and Process times of the One-Sided Welder, the throughput of the line will increase providing that it is not reduced below the span times of the Stations after the welder.

The blockage caused by the stiffener welder in Station 5 is due to the variation in the number of longs that are on the panels welded in this station. Although averages were used to characterize the variable work content of the panels, the results of the simulation model show that the use of averages is not the best way to characterize this work. Figure 4 shows a histogram of the number of longs per panel built on the Panel Line.

Figure 4. Number of Longs per Panel

The average number of longs per panel is 11.6, however, almost 50% of the panels have 13 longs and only 5% of the panels have 12 longs. The additional long requires one extra pass with the stiffener welder. This increases the Span and Process time for the station as seen in Table 4, which causes the blockages shown in Figure 3. The Process Improvement Team understood that the extra longs would increase the station span time but felt that the 35% of the panels which have less than 13 longs, and in some cases as few as 3 longs, would draw the average process time closer to that of a 12 long panel. This was difficult to test without using the computer simulation model. The stiffener welder welds 12 longs in 218 minutes in the “To-Be” process. Since 4 longs are welded in a pass during the 218 minutes the average pass takes approximately 73 minutes. It would take 4 passes to complete a 13 long panel; therefore, the process time would be 292 minutes for this station when the extra pass is made. Table 4, however, shows that the average process time for the stiffener welding station is 236 min. The model indicates that the assumption made by the Process Improvement Team was correct. The average
is reduced by the 35% of the panels with less than 13 longs. However, it is not enough to bring the average to that of a 12 long panel.

There is a second factor constraining throughput in the middle of the line. The Average Process time for the fitting work in Station 4 is less than the Average Process time for the welding in Station 5. The imbalance in work content between stations causes blockage and idle time, contributing to the higher cycle time of the line. The imbalance is further magnified by the scheduled assembly sequence of the panels. When very low work content panels follow very high work content panels, large blockages in the line are created in the upstream stations. If high work content panels follow low work content panels, idle time develops in the downstream stations. The varied scheduling of panels in such a sequence produces an “accordion effect” where gaps between panels open and close on the line. These gaps increase the cycle time of the line. Therefore, it is not only the variation in work content in each individual station that is important to understand, but the variation in work content and sequencing between all of the stations which influences the dynamics of the line. Averages were used by the Process Improvement Team to overcome the difficulties in manually analyzing this variation, but the simulation shows that understanding the variation is a necessary part of understanding the line.

The same situation occurs in the Station 7 and 8 weldout stations. These stations also interact with Station 5 to create blockages and higher span times in almost all of the stations on the line.

Effect of Variation on Scheduling

The variation of work content created problems in the scheduling of panel removals from the line which was realized once computer simulation was used to analyze the “To-Be” process. One of the main objectives in employing a 4 hour line was the ability to be able to schedule the removal of completed panels from the line at 4 hour intervals. Figure 5 shows the time between lift-offs for the variable work content panels.

Figure 5. Time Between Panel Lift-Offs

![Diagram showing time between finished panels in hours]

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Figure 5 shows that panels are not being completed at regular 4 hour intervals and that the spread in lift off times ranges anywhere from a few minutes to 15 hours. The variation of work content and the removal of panels from four stations on the line make this very hard to analyze manually. The computer model, however, is quite capable of handling this task.

Possible Changes to Panel Line to Achieve 4hr Cycle Time

Once it was determined that the variation in work content resulted in an Average Cycle time per panel of more that 4 hours, four possible options for further reducing the line’s cycle time were investigated:

- Change Panel Design/Take Work off Panel Line
- Reduce Process Times
- Add Automation (Robotics)
- Resequence Order of Panels

Change Panel Design/Take Work off Panel Line

Because of the timing of this project, it was decided that the design of the panels currently scheduled to be built on the line could not be changed. Panels for the fourth of a successful seven ship contract were being constructed on the line, so the cost/benefit of utilizing the resources to make the changes to the last three ships was not very good. In addition, there was an understandably high resistance to making changes to the product model when every change meant the potential of jeopardizing an already successful project.

Taking panels that had a higher work content than the reference panel off of the line also was not a feasible option at this time. The panels would have to be built in build locations already heavily utilized to construct other products. The Panel Line is one of the most efficient build locations within the yard for building flat products. A penalty in efficiency occurs by moving the panels from the Panel Line to one of the flat build locations. This penalty is justified as long as the gains in efficiency from moving work off the line offset the efficiency losses due to assembling the panels elsewhere. There is a point, however, when this tradeoff no longer becomes advantageous.

Reduce Process Times

Reducing the process times was a second option investigated by the Process Improvement Team. In order to create the “To-Be” process, however, a substantial amount of time had already been cut out of the existing processes. These cuts in time also came at a substantial cost. In order to assess the additional reduction in process times necessary to achieve the objective of a 4 hour cycle time for panels with variable work content the computer simulation model was again employed.

The process time per plate, deck socket, long, and web for each station was reduced in increments of 5% in order to reduce the Average Process time per panel. While this was occurring, resource and location utilizations were being monitored to determine the balance in per-unit process time reductions that would allow for the best usage of resources and equipment. This is yet another
advantage of computer simulation. As changes are made, the effects of those changes on the system are immediately evident. Table 5 shows the additional percent decrease in per-unit process times at every station that would be necessary to achieve the objective of a 4 hour line (with variable work content panels) and utilize the resources in the best way possible.

Table 5. Additional Per-Unit Process Time Reductions Required by Station

<table>
<thead>
<tr>
<th>Percent Decrease in Process Unit Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Plate Fitting</td>
</tr>
<tr>
<td>2. and 2. Deck Sockets</td>
</tr>
<tr>
<td>3. One-Sided Welding</td>
</tr>
<tr>
<td>4. Layout</td>
</tr>
<tr>
<td>5. Perimeter Burn</td>
</tr>
<tr>
<td>6. Stiffener Fitting (Press)</td>
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<tr>
<td>7. Stiffener Fitting (Manual)</td>
</tr>
<tr>
<td>8. Stiffener Welding</td>
</tr>
<tr>
<td>9. Web Fitting</td>
</tr>
<tr>
<td>10. Weld Out 1</td>
</tr>
<tr>
<td>11. Weld Out 2</td>
</tr>
<tr>
<td>12. Inspection and Ship</td>
</tr>
</tbody>
</table>

The per-unit process time would have to be reduced in Stations 3 through 8, and a 30% reduction in per-unit process time is necessary in Station 5. Stiffener welding is a machine-based process. The reduction in time would have to be achieved by speeding up a machine that is already running at its optimum operating level based on the welding parameters of the material. This would be impossible with the existing welder and the material used to fabricate the panels.

Even if the further reductions could be made in the process, the results of the simulation show that the blockages would not be totally eliminated. Figure 6 shows the Location States for the 4 hour variable panel model with reduced times.

Figure 6. Location States for the 4.0 Hour Line with Reduced Process Times
The blockage is less than that shown in Figure 3, but has not been eliminated. The variability in the panels still holds up the line. In order to reduce the process times in each station just to achieve the location states shown in Figure 6, additional manpower and equipment would be necessary. These resources would be unutilized while the line is blocked. A penalty in resource utilization would be paid in order to achieve the 4 hour line.

Add Automation (Robotics)

A third option of using robotics to eliminate the bottlenecks in the line is being investigated as part of another simulation project. The preliminary results of the project indicate that the addition of robotics to assist in the fitting of stiffeners and weldout of webs would provide the same throughput rate as the existing system, but at a substantial savings in labor costs. The benefit in adding the automation, therefore, is not a decrease in panel cycle time over manual panel line processes, but a reduction in manual labor. Proper balancing of the panel work contents between stations would still be necessary in order to achieve the best possible panel cycle time.

Resequence Order of Panels

Resequecing the order of the panels is probably the easiest option to implement, but the most difficult of the four options to simulate. Changing the order of the panels to smooth out the flow of the work might reduce the average per panel cycle time to 4 hours without expensive equipment or process changes, however, many more variables come into play when optimizing the system in the model. Currently the panels are scheduled for the line by the need date of the next assembly. If the panel is late, the start of the next assembly is late. This may cause a ripple effect leading to the late erection of a block. There is some float in this date, but the amount is dependent upon current workload, complexity of the products, resource levels of the yard, and available storage space. An estimate of the amount of float in start and complete dates for the panels is necessary in order to determine the window in which the panel can be moved to accommodate work flow. Because of the dynamics of the variables involved, computer simulation is a necessary tool in the analysis of this window.

The position of the panel on the line over time also plays a role in resequencing the panels. As mentioned earlier, panels are pulled off the line as they are completed in four places. The lift-offs between these four areas need to be coordinated in order to make the best use of line space and schedule. Trying to juggle all of the variables such as work content and process time necessary to balance the line at the take-off points will be difficult even with the use of computer software.

For these reasons, the project team is investigating the use of optimization software to drive the sequencing of the panels. The optimization package included with ProModel is SimRunner. SimRunner takes input constraints from the user and optimizes the model to those constraints through the use of factorial design of experiments and other optimization algorithms. Once the constraints are specified, SimRunner works on its own, reducing the time necessary for the user to perform the experiments. Because of the complex logic involved in determining the possible orders of the panels, some changes to the model will be needed to interface with SimRunner beyond the normal interactions. The changes necessary to perform these interactions and the amount of time required to make the changes are currently being investigated.
Conclusions

As the level that shipyards investigate their processes for possible improvements becomes more detailed, the tools typically used to analyze them become more cumbersome to employ. Assumptions are used to simplify the processes in order to make them more manageable to flowchart and understand. Sometimes the simplification of the processes can inadvertently lead to a loss of detail that is necessary to completely understand the system. Capturing the variation in process times and work content is also very important to creating a clear picture of the manufacturing process. Increases in personal computer processing speed and the development of user-friendly computer simulation software now provide shipyards with an ability to not only include a higher degree of detail in their analysis, but a way to capture the variation in process and work content.

NASSCO's use of computer simulation proved to be a valuable tool in the analysis of the company's Panel Line. First and foremost, it demonstrated the complexity of the dynamic interactions between stations, products, processes, and schedules. In order to simplify the paneling operations for manual process analysis techniques, the Panel Line was viewed as a rather straightforward process. Panels were moved into a station, processed, and then moved to the next station when it was time for the line to move. The stations with the highest span time determined the cycle time of the line, so the focus was to optimize the processes in these stations to meet the performance objectives. When working with averages and constant numbers this happens to be the case. When variation in the process times, products, and pull locations exists, however, the cycle time cannot be obtained using the same methods. Sub-optimizing the individual processes and line stations often can lead to performance degradation of the overall system if it is not known how the individual components interact to affect the system's performance. Simulation software is very capable of keeping track of all of the variables and interactions involved in the overall operation of the line. Variance in the products and process times can be introduced to better understand their role in planning and forecasting the performance of the system, while changes made to the model can be immediately quantified. It is advantages such as these that make computer simulation an important tool in the analysis of complex shipbuilding processes, and it is the understanding of these processes, which will help yards produce cost competitive ships into the next century.