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A SYNTHETIC DESIGN ENVIRONMENT FOR SHIP DESIGN†

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INTRODUCTION

Rapid advances in computer science and information system technology have made possible the creation of synthetic design environments (SDE) which use virtual prototypes to increase the efficiency and agility of the design process. This next generation of computer-based design tools will rely heavily on simulation and advanced visualization techniques to enable integrated product and process teams to concurrently conceptualize, design and test a product and its fabrication processes. This paper summarizes a successful demonstration of the feasibility of using a simulation based design environment in the shipbuilding industry.

As computer science and information science technologies have evolved, there have been many attempts to apply and integrate the new capabilities into systems for the improvement of the process of design. These systems go by names like Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), Computer-Aided Engineering (CAE), and Computer-Aided Systems Engineering (CASE). We see the benefits of those efforts in the abundance of highly reliable, technologically complex products and services in the modern marketplace. Furthermore, the computer-based technologies have been so cost effective that the improvements embodied in modern products have been accompanied by lowered costs.

Today the state-of-the-art in computerized design has advanced so dramatically that the focus is no longer on merely improving design methodology; rather the goal is to revolutionize the entire process by which complex products are conceived, designed, fabricated, tested, deployed, operated, maintained, refurbished and eventually decommissioned. By concurrently addressing all life-cycle issues, the basic decision making process within an enterprise will be improved dramatically, leading to new levels of quality, innovation, efficiency and customer responsiveness. By integrating functions and people within an enterprise, such systems will change the fundamental way American industries are organized, creating companies that are more competitive, creative and productive.

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TRADITIONAL PRODUCT DESIGN CYCLE

As indicated in Fig. 1 below, the product life cycle consists of five phases: (1) requirements definition, (2) concept development and design, (3) manufacturing, (4) test and verification, and (5) operation. (The operational phase can be thought to include product utilization, maintenance, refurbishment and disposal.) Although the traditional, narrow view of product development focused on phases (2) through (4), today it is well recognized that the product development cycle must include both the front-end, wherein some basic trades between user needs and system capabilities are made, and the tail-end, which contains much of the total life cycle cost and all of the value delivered to the customer.

Traditionally, product development has been a sequential process, starting with a perceived customer need that is translated into requirements and ending with a product in operation, hopefully satisfying the perceived need. As shown in the figure, iterations of the design can take place at any point along the process; but changes made to the product late in this cycle are inevitably costly. One of the basic objectives of SDE is to avoid such costly redesign by enabling designers to concurrently address all phases of the life cycle.

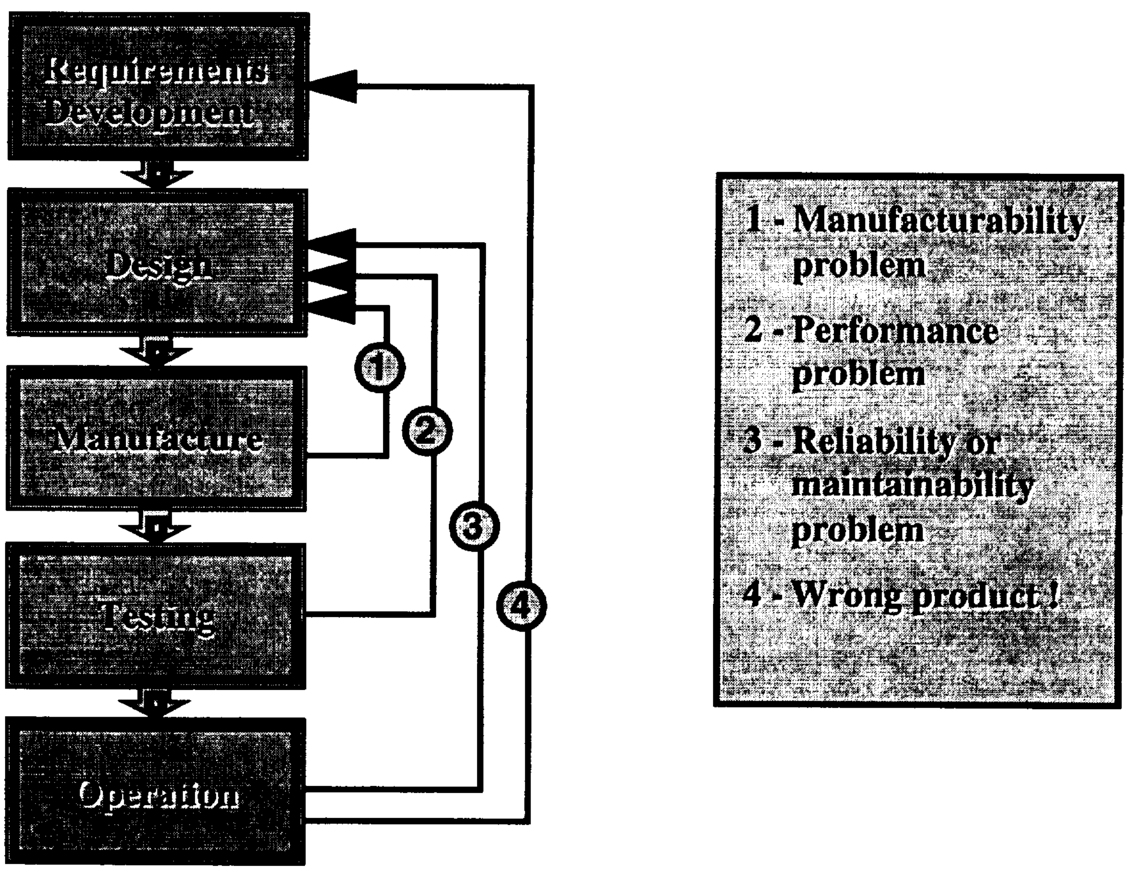

Figure 1 - Linear, sequential product development cycle.

PRODUCT DESIGN CYCLE OF THE FUTURE

As indicated in Fig. 2, the fundamental way of accomplishing the goal of transforming the product development process is to perform product virtual prototyping. Prototyping is not a new concept -- in fact, both NASA and the Department of Defense historically have used this approach for many of their major procurements -- but in the past the prototypes were physical manifestations of the end product. Consequently, such prototypes were themselves costly and time-consuming to create. In synthetic design environments, however, a computer-generated or *Virtual Prototype (VP)* of the product is created. This virtual representation of the design can then be assessed and evaluated, using appropriate simulations of the various phases of the life-cycle. As we shall illustrate in the remainder of the paper, use of virtual prototypes enables true concurrent engineering of a product, which can result in dramatic improvements in quality, innovation, efficiency and customer responsiveness.

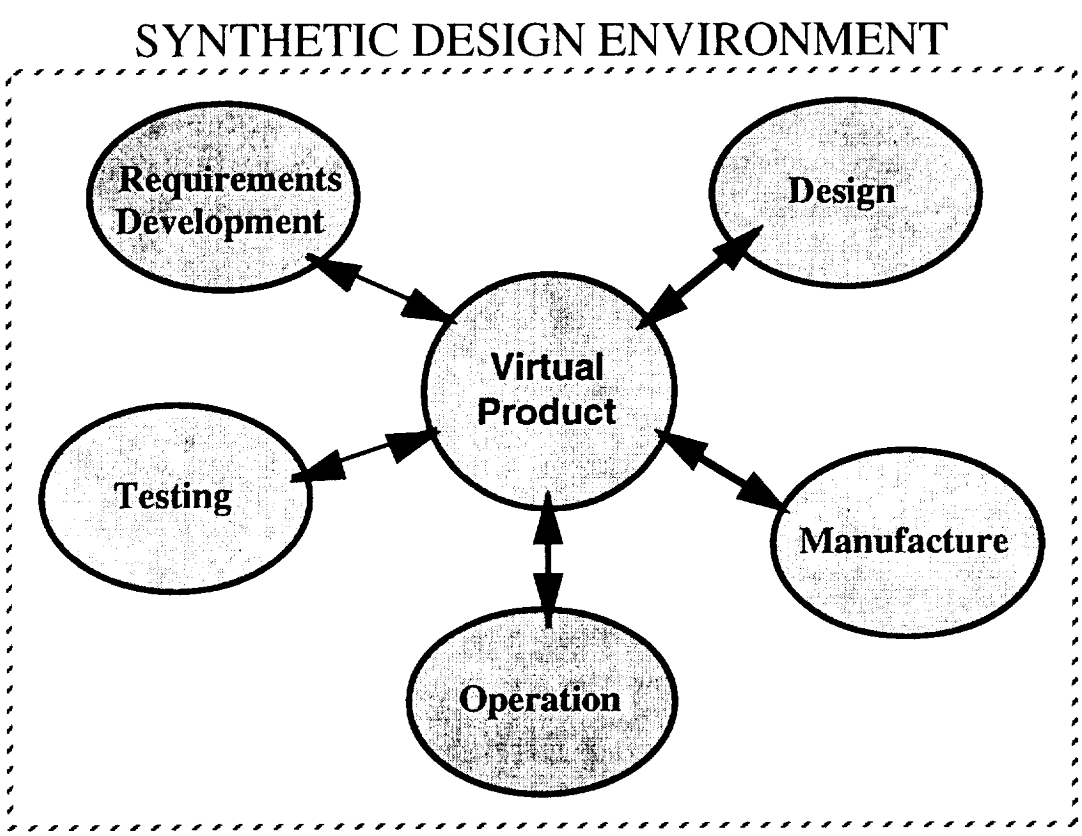

Figure 2 - Future, concurrent product development cycle.

EVOLUTION OF COMPUTER AIDED DESIGN

As outlined in Fig. 3 below, the role of computers in the design process has been evolving over the last thirty years. Initially, they were used by engineers exclusively for the analysis of the design; visualization and design capture were done on drafting tables. These analyses were each individually crafted on the computer codes and were one-of-a-kind products. The first major change was brought about by the introduction of computerized drafting tools, which took the designers away from the drafting tables and put them in front of special-purpose computer display scopes. There the designers captured their designs as electronic drawings on the computer screen by using light pens and special key pads. In parallel, the analysis community was making great strides in creating general purpose analysis codes, e.g. NASTRAN, and computer programs that linked several analyses together were written to perform integrated design and optimization. This was followed by a flurry of development of general purpose codes that became products themselves. These tools harnessed evolving computer technology to perform computer aided engineering, computer integrated manufacturing, and computer aided software (and system) engineering.

In the last decade, computers have become extremely fast at performing calculations and displaying or rendering images. These capabilities have brought about extraordinary advances in the types and levels of analysis that can be undertaken by computers and in the visualization of the results of these analyses. Consequently, computer simulations are now routinely conducted to address extremely complex and detailed physical behavior. Simultaneously, CAD, CAE and CIM tools are being linked together to provide powerful systems for the aiding of the design, engineering and manufacture of products. Added to these advances is the most recent development of synthetic environments, in which designers can immerse to better visualize and understand the product, and in which the products can be "operated" or tested in a simulated real world environment. The confluence of these recent trends is bringing about the next step, the development of synthetic design environments for simulation aided (based) design.

- **Uncoupled Analyses**
- **CAD**
- **Integrated Design (Optimization)**
- **CAE / CIM / CASE**
- **Engineering Simulations**
- **Linked CAD / CAE / CIM**
- **Synthetic Environments**
- **Synthetic Design Environments and Simulation Aided (Based) Design**

Figure 3 - The evolving role of computers in design.

NEXT GENERATION DESIGN SYSTEMS

As noted in Fig. 4 below, we refer to the next generation of computer-based design systems as ***Simulation Based Design (SBD) Systems*** or, alternately, as ***Synthetic Design Environments (SDE)*** .

Simulation based design refers to one central aspect of these new systems -- the emphasis on simulations as a unifying method of representing and analyzing products throughout their life cycle. As used herein, "simulation" has a broad connotation and encompasses modeling/analysis for various purposes and at various levels of fidelity. SBD will utilize and combine virtual, constructive, engineering and physics-based simulations within a single framework to create different views of the product and its behavior throughout its life.

Synthetic design environment highlights another fundamental aspect of the systems -- the creation of artificial or virtual design environments within which diverse representations and models of the product are created, viewed, analyzed and operated. In other words, SDE is the design space for building and conducting product simulations. These simulations may include approximate parametric models for rapid design trades and requirements development; complex, detailed performance prediction models; virtual models for real-time war gaming; manufacturing process models; and virtual reality representations in which customers and designers can examine the product prior to its actual physical creation.

<u>Next generation of computer-based design systems:</u>

- **Simulation Based Design (SBD) Systems**
- **Alternately, Synthetic Design Environments (SDE)**

- **Why Simulation?**
  - **Emphasis on simulations as a unifying method of representing and analyzing products throughout their life cycle.**
- **Why Synthetic?**
  - **Creation of artificial or virtual design environments within which diverse representations and models of the product are created, viewed, analyzed
and operated.**

Figure 4 - Next generation design systems will be simulation based, synthetic design environments.

SIMULATION BASED DESIGN

As shown in Fig. 5, the central concept in simulation based design is the creation and use of Virtual Prototypes in synthetic environments to define, develop, produce, test and maintain a complex system. A Virtual Prototype (VP) is a computer generated model of a product capable of functioning properly and appearing realistically in a responsive virtual environment, representative of the physical environment in which the actual product will or may function. Thus, a VP must have the proper geometry and a realistic appearance. It must also respond to the synthetic environment and function in it as it would in the real physical environment.

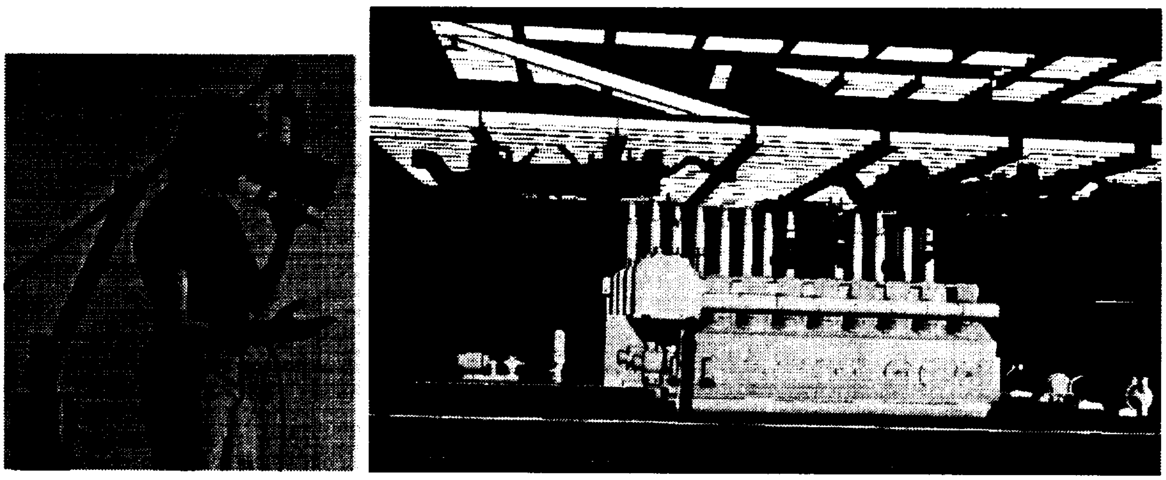

Figure 5 - Virtual prototypes in synthetic environments are central to SBD.

KEY SBD CAPABILITES

Although the constituent capabilities of SDEs are still evolving, several critical features of such systems have emerged. Figure 6 shows five of these key attributes: (1) an immersive design environment to facilitate collaborative product viewing and interrogation; (2) high fidelity computerized, physics-based simulations to properly model the performance of the product; (3) distributed interactive simulations to enable the product to be tested or operated in a synthetic environment; (4) a visual programming environment in which engineering and manufacturing analyses can be rapidly linked together; and (5) an integrated, "smart" product model that captures the data, models and analyses needed to represent the design and the processes by which it is produced.

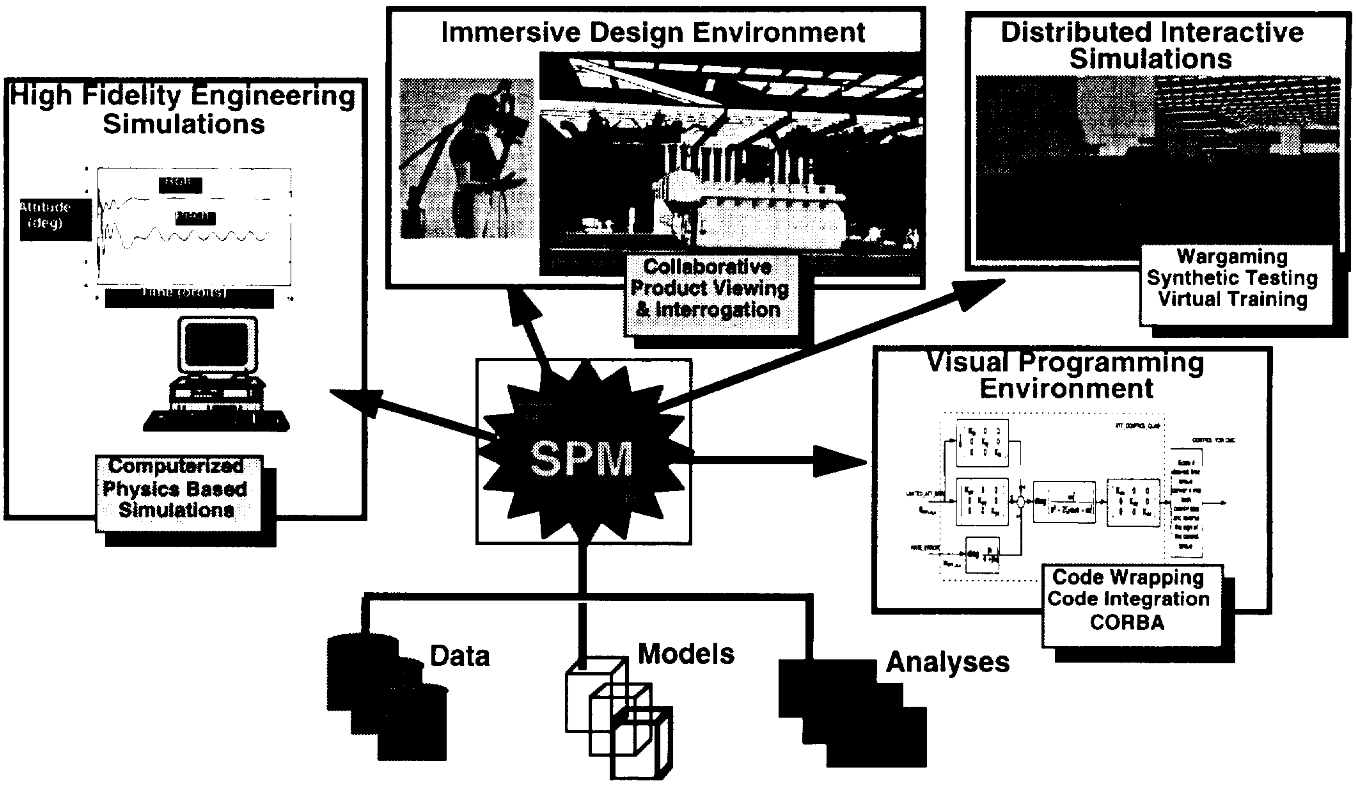

Figure 6 - Integration of key SBD attributes.

NETWORKING EXPERTS

Implicit in the design environments of the future is the concept illustrated in Fig. 7; i.e. that the environment will support design teams that are geographically distributed. Modern computer network technology enables us to connect design team members who are not physically collocated. Similarly, the technology enables the design itself to be physically distributed among data sets residing on computer hardware that is not collocated. Typically, even the analyses codes can and will be located on different machines in different physical locations.

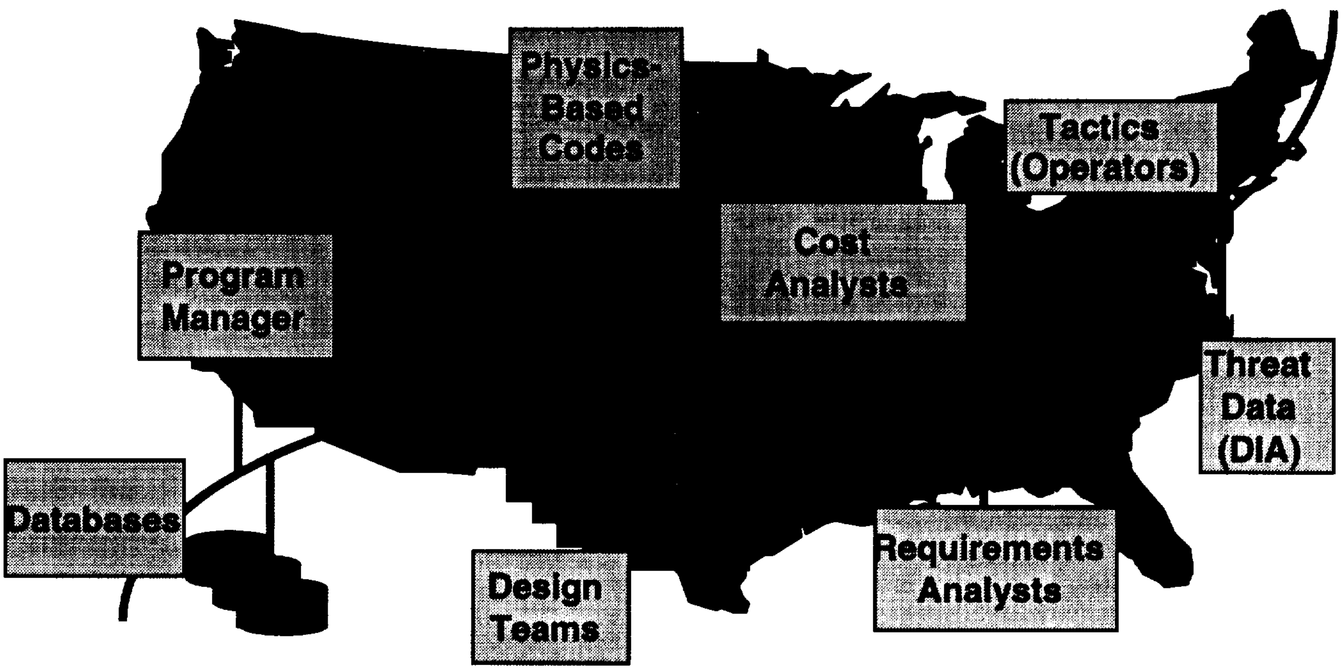

Figure 7 - SBD will tie together geographically distributed design teams.

DEMONSTRATION OF SIMULATION BASED DESIGN

An intensive demonstration of how an advanced synthetic design environment might work in the shipbuilding industry was conducted in the summer of 1995 by two teams funded by the Advanced Research Projects Agency. The remainder of this paper addresses the demonstration conducted by a team from Lockheed Corporation, Science Applications International Corporation and Newport News Shipbuilding. The design environment was given the name, Simulation Based Design (SBD). As shown in Fig. 8 below, SBD was used to conduct a design exercise for a notional military roll-on/roll-off ship (denoted the Notional Baseline Ship, NBS), having amphibious lift capability.

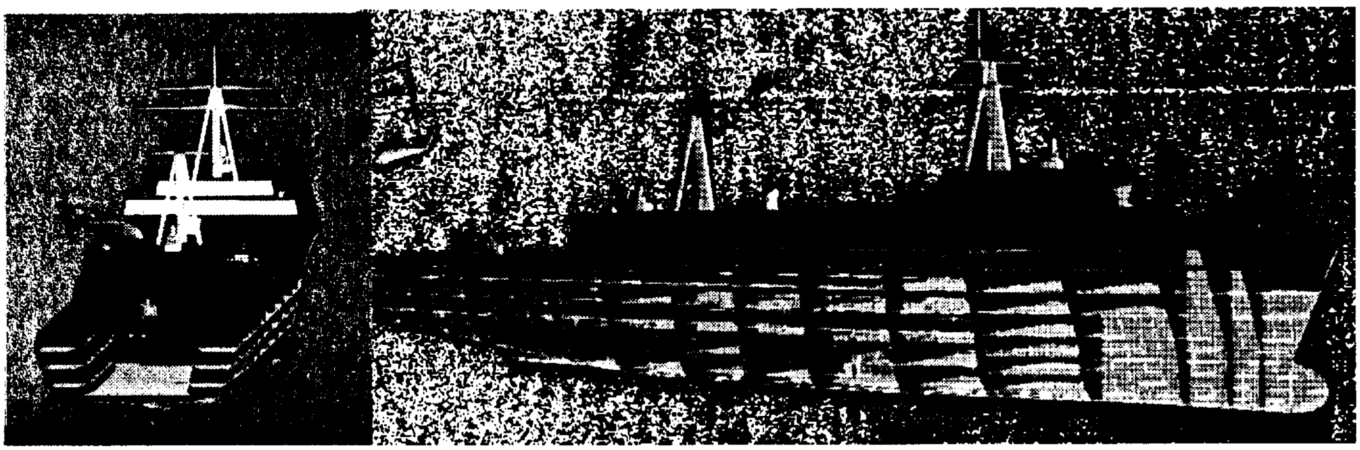

Figure 8 - The Notional Baseline Ship, NBS.

SHIP DESIGN DEMONSTRATION SCENARIO

As illustrated in Fig. 9 below, the ship design demonstration scenario consisted of seven elements or stages: (1) mission analysis , (2) propulsion system selection (featuring use of the smart product model), (3) collaborative design, (4) distributed interactive simulation, (5) multi-disciplinary analysis, (6) manufacturing analysis, and (7) cost and risk analysis.

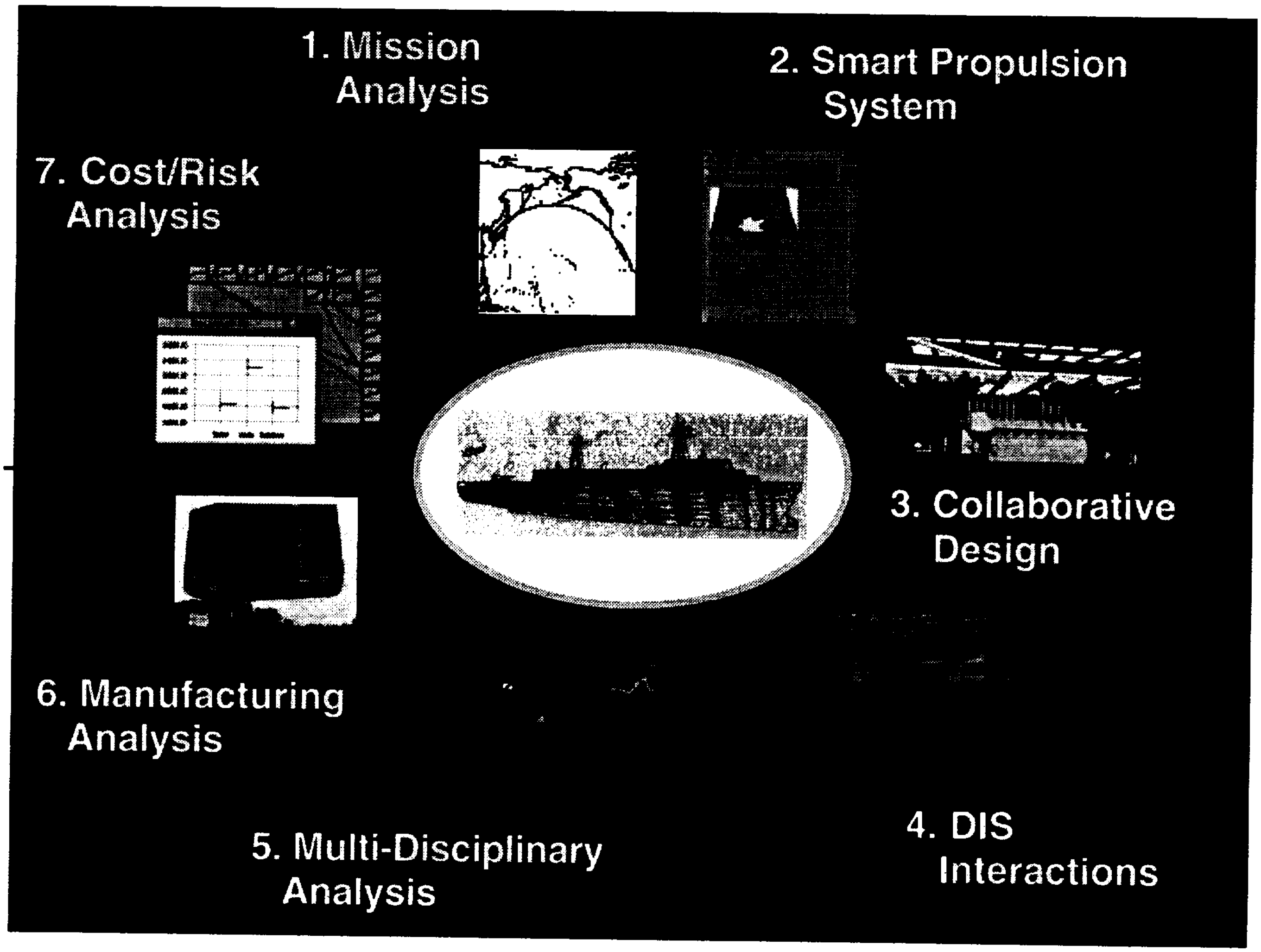

Figure 9 - Segments of the SBD ship design demonstration.

MISSION ANALYSIS SEGMENT

In the first segment, data on the existing NBS design are used in an operational analysis to determine the required speed change and the associated engine horsepower change. Concurrently, a first estimate is made of the associated cost. As seen in Fig. 10, this segment begins with a hypothetical mission requirement to deliver men and material from ports in the continental United States to the Korean peninsula within a prescribed time period. A presumed fleet of existing NBS must be evaluated to determine the ability to perform this mission.

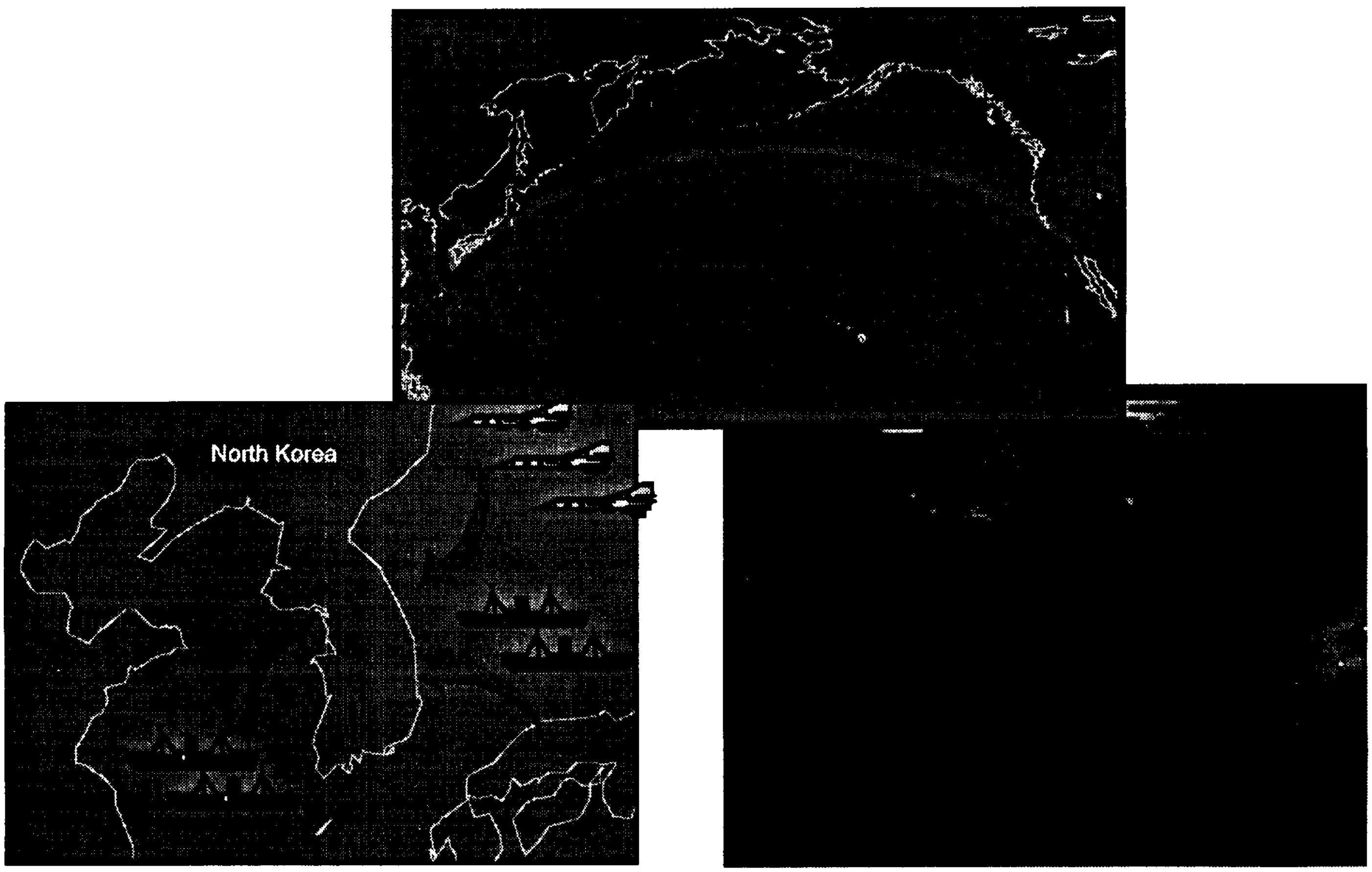

Figure 10 - Hypothetical mission for the NBS.

MISSION ANALYSIS USING SPEED-OVER-GROUND MODEL

Using existing data on the NBS, SBD performs a rapid mission analysis. As shown in Fig. 11, Monte Carlo simulations of the ships' transit are conducted, using statistical data on sea state along the specified route and NBS resistance curves, derived from hydrodynamic analyses. The data and models for this speed-over-ground (water) analysis are "stored" in (i.e., associated with) the product model for the NBS. This product model is referred to as a "Smart" product model, in part, because such associations can be made to assure that appropriate data and analyses are automatically accessed whenever the design is interrogated.

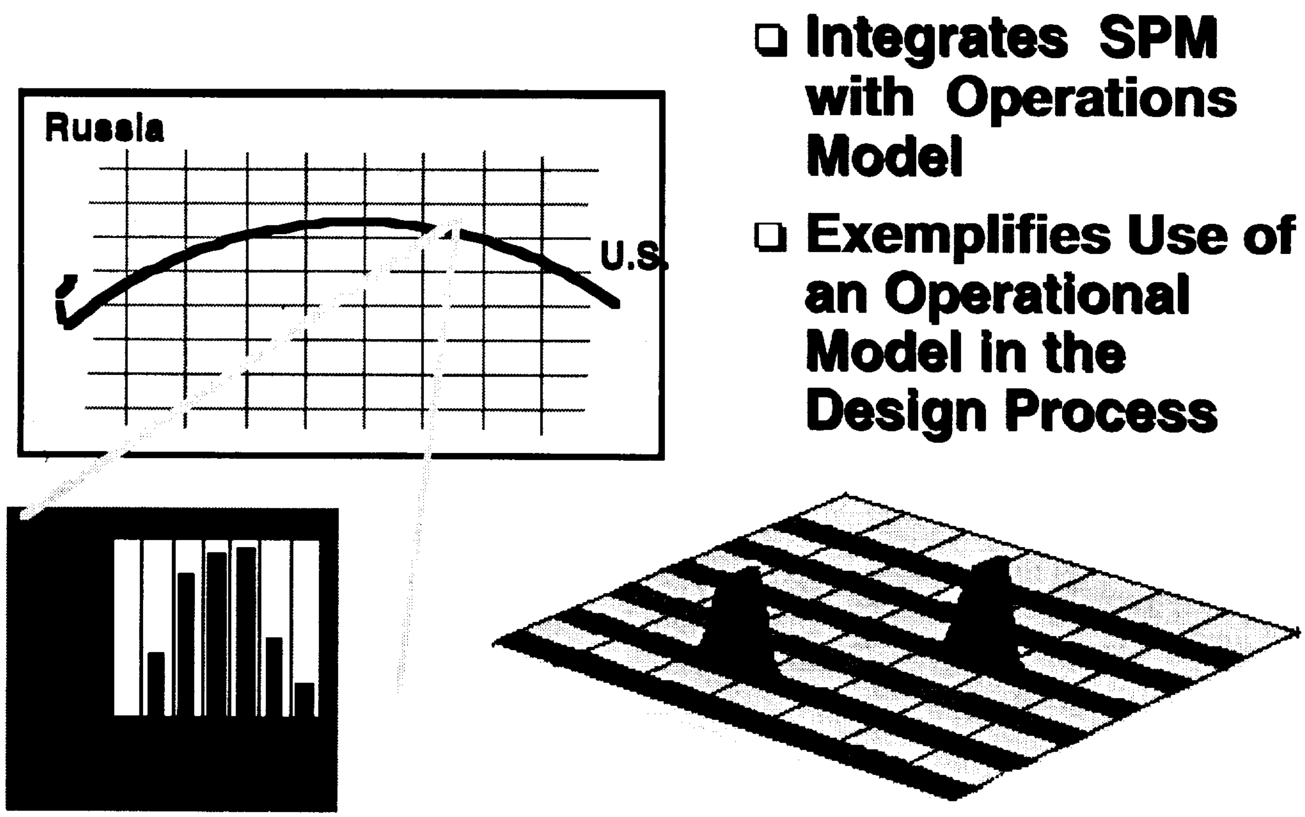

Figure 11 - Monte Carlo analyses of the mission are performed using data and models stored in the Smart Product Model for the NBS.

MISSION ANALYSIS - ALTERNATIVES FOR INVESTIGATION

After the initial analysis shows that the existing fleet cannot meet the required material build-up, several alternatives are postulated for further consideration. Two of these alternatives -- increase the number of NBS in the fleet (i.e., build more ships), and refit the NBS to increase its speed -- are carried forward for more detailed analysis. Figure 12 shows the results of those analyses: three additional ships would be needed to satisfy the requirement; or the existing ten ships would have to increase their top speed from nineteen to twenty-two knots. The mission analysis also determines that an engine shaft horsepower of 45,000 is required to propel the NBS at the top speed of twenty-two knots.

- **Number of Ships**
- **Speed**
- **Capacity**
- **Decommission Fewer Ships**

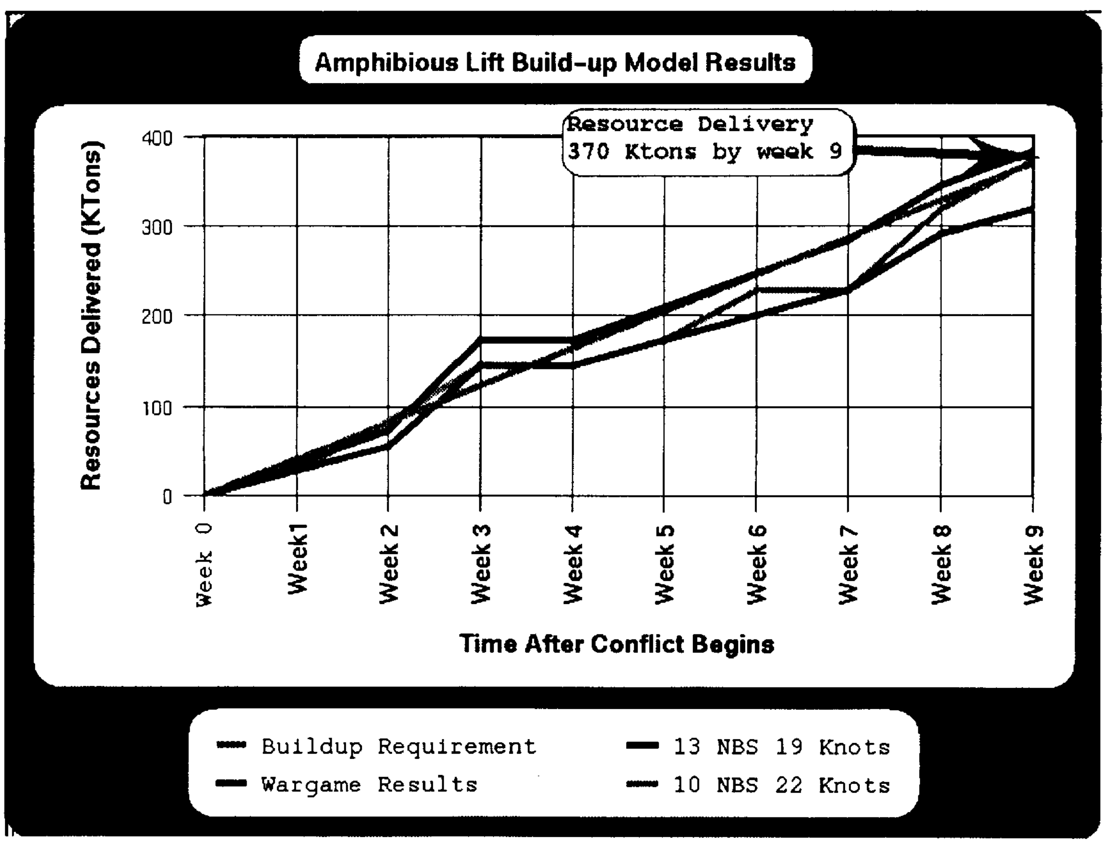

Figure 12 - Results of SBD Mission Analysis.

MISSION ANALYSIS - COST AND RISK ANALYSIS

For the two chosen "solutions," SBD is used to generate a rapid cost and risk analysis. The necessary data are automatically gathered from the Smart Product Model. The associated risk analysis code determines the expected cost of each alternative and the distribution about that expected value. As shown in Fig. 13, the alternative of increasing the speed of the NBS appears to be better than the building of more ships, and appears to be only slightly more costly than the baseline. The remainder of the demonstration explores the faster-ship alternative in more detail. In effect, an actual redesign is performed to confirm the viability of increasing ship speed, explore the impact of the design change on other ship performance attributes, determine the impact on manufacturing and develop a detailed cost estimate to support or refute the conclusion of the preliminary cost/risk analysis.

- **Uncertainty/Risk Management**
- **Recognizes SPM Dependencies**
- **Actuates Engineering Models**
- **Tracks Design Change Impacts**

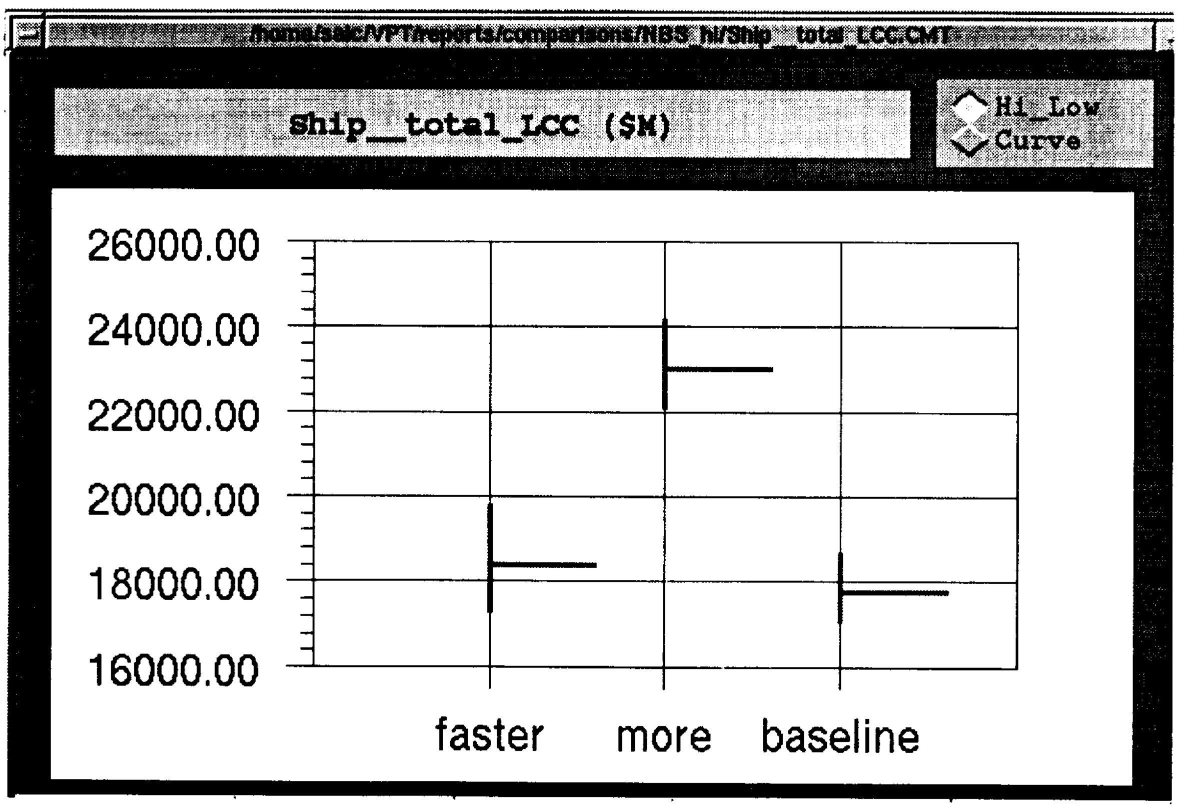

Figure 13 - Cost and risk analysis within SBD is the key to making informed design decisions.

SMART PRODUCT MODEL

In the industry of the future, a model of a product will be constructed at the instance of its conception. This model will be expanded, refined and invoked throughout the product's life to capture and evaluate the evolving design. This model is sometimes called an Integrated Product and Process Development Model (IPPDM) because it contains descriptions of both the product and the processes required to develop and produce it. We call the model a "Smart Product Model" (SPM) to denote that higher level product information is captured; i.e., it includes not only a physical description of the product but also the data, models and analyses necessary to fully characterize and evaluate the product. The model is also "smart" in that it knows where, among a myriad of voluminous and geographically distributed electronic databases, to find the data it needs to perform and display the results of any analysis or simulation called for at any given time. The SPM is "smart" in a third sense; it is structured as a collection of objects, each of which has its own set of associated attributes, behaviors and characteristics. For example, if a sub-component of the system/product is replaced, performance and cost models associated with the new and old components are automatically replaced as well. As shown in Fig. 14, the SPM unifies product and process information shared within the enterprise, and acts as a real-time, distributed spreadsheet providing and controlling product and process information across the enterprise throughout the product life cycle.

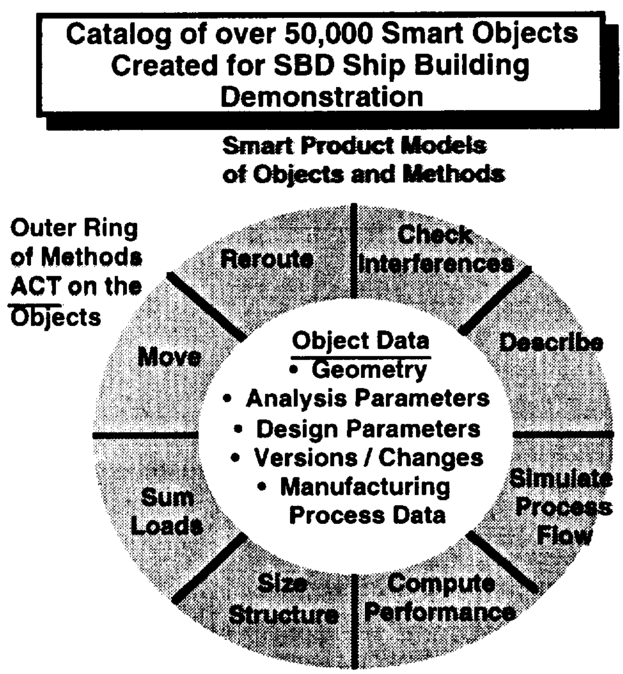

Figure 14 - The Smart Product Model links data and processes in an object-oriented structure.

SMART PRODUCT MODEL - CONTINUED

As shown in Fig. 15, the product is represented in a logical hierarchy in the Smart Product Model. Thus, in the demonstration the ship is an object consisting of other objects, such as the bridge and the engine room. In turn, each of these objects consists of other objects, e.g., the engine room contains an engine, a heat exchanger, etc. In the SBD, one can change the design by altering aspects or features of the constituent objects or by completely replacing old objects with new. The user interface makes the swapping of objects as easy as a "drag and drop" operation on a desk-top personal computer.

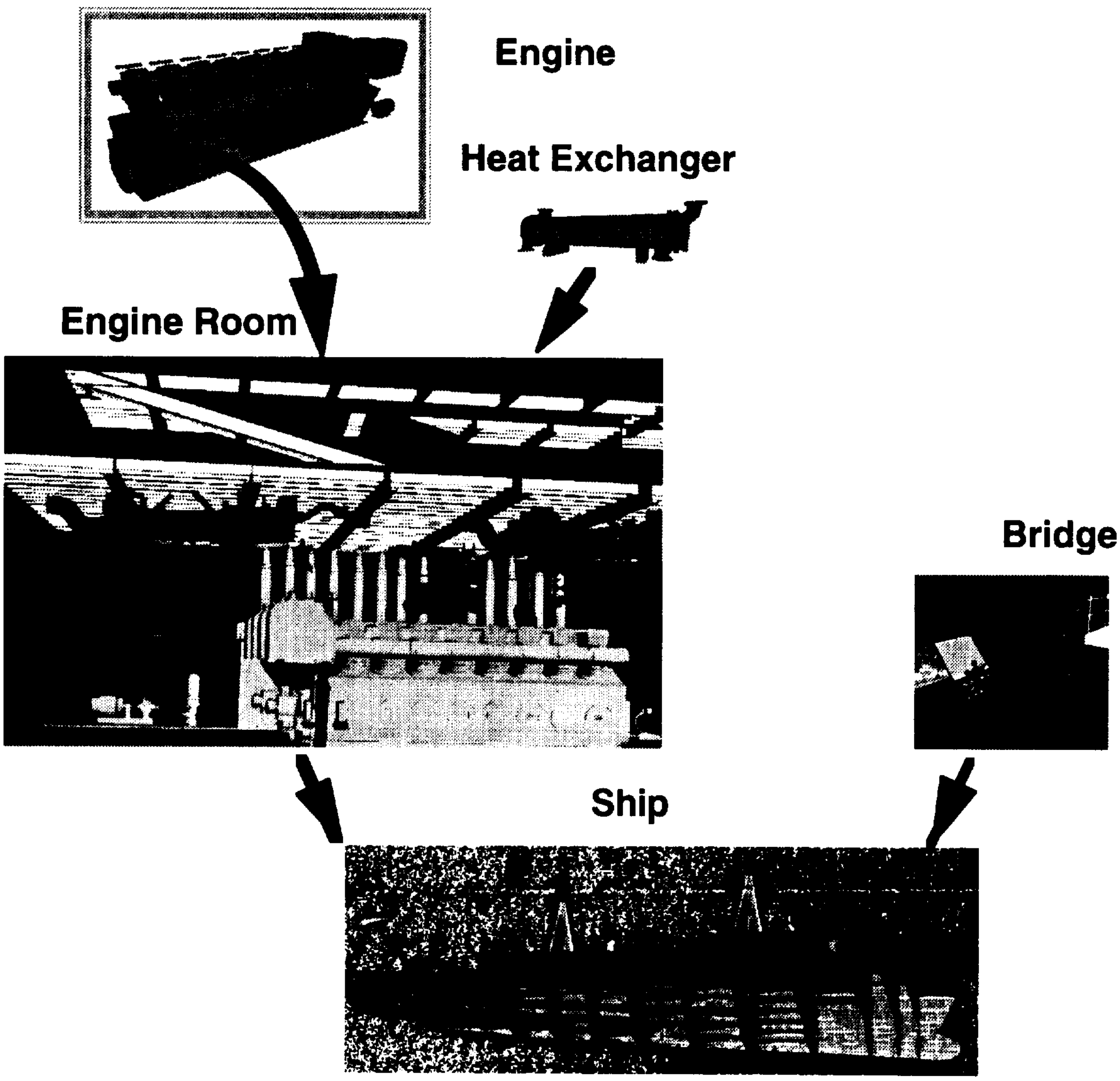

Figure 15 - Drag and drop hierarchy of smart objects populate the Smart Product Model.

PROPULSION SYSTEM SELECTION

From this point forward in the demonstration, the synthetic design environment is used to visually design changes and to examine their impact. This segment employs electronic commerce via the Internet to select an engine replacement capable of providing the necessary horsepower. The product model data associated with the engine are brought into the Smart Product Model (SPM) on the complete NBS with a simple "click and drag" operation, and the new engine automatically appears in the SDE with associated piping automatically re-routed. The SPM automatically invokes and executes associated analyses that identify and flag in the SDE any remaining equipment fouls. Other analyses are automatically executed that determine if the capacity of an existing heat exchanger is inadequate. This leads, in turn, to selection of a replacement for the heat exchanger using electronic commerce, the SPM and the SDE.

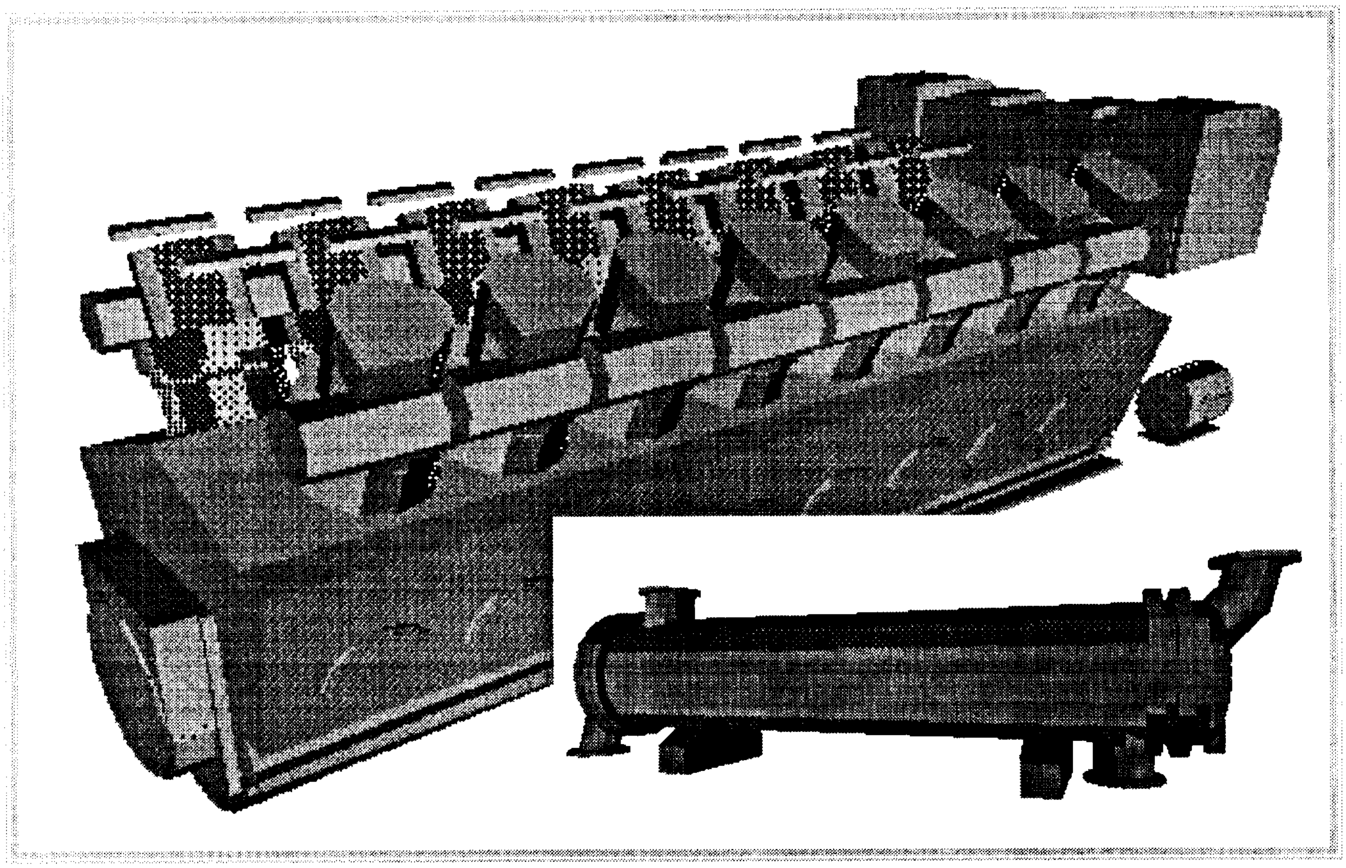

Figure 16 - Engine and heat exchanger models are selcted via Commerce Net and swapped into SPM.

COLLABORATIVE DESIGN

In this segment of the demonstration scenario, a Propulsion Engineer and an Arrangement Specialist are simultaneously immersed in the Virtual Design Environment (VDE) to resolve the fouls caused by placement of the new engine and heat exchanger. Both members of the design team "enter" the engine room shown in Fig. 17. One participant uses a FakeSpace BOO3C, stereo, high-resolution color visualization system while the other uses a Virtual Research Eyegen3 Head Mounted Device. Using a three-dimensional pointer, the Arrangement Specialist selects and moves a bulkhead, associated equipment and deck grating to accommodate the larger engine. Piping re-routing is performed automatically while other arrangement changes are commanded directly by the immersed design team. By obtaining virtually instantaneous three-dimensional design updates, the team is able to quickly make arrangement changes, and investigate and verify impacts. One additional feature illustrated in this segment is automatic notification of other, non-immersed members of the design team that a design change was made in an area that might impact them.

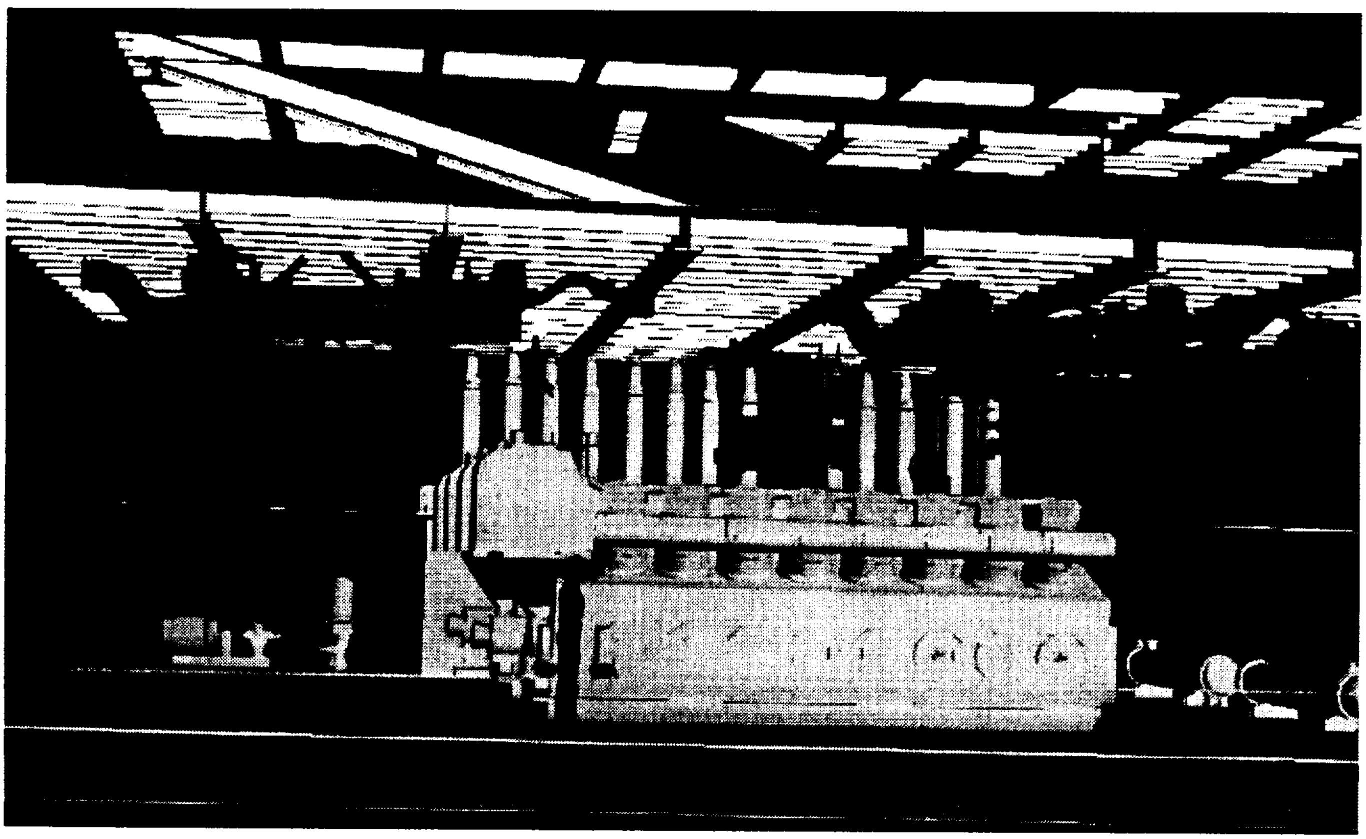

Figure 17 - Engine room as displayed in the Virtual Design Environment.

DIS INTERACTIONS

In response to the design change notification issued in segment 3, the designer responsible for the stowage compartment above the engine room is alerted to a structural change that reduces the volume of the stowage compartment in certain areas. To determine whether this change compromises the ability to load armored tanks, a Distributed Interactive Simulation is invoked wherein an M1 tank driver attempts to drive his vehicle aboard the NBS and into the stowage compartment. In Fig. 18, the tank is shown driving up a ramp in the interior of the NBS. The unique features of this demonstration are: (1) The driver and his simulator are located in a physically different place from the rest of the participants so that his entire view of the ship is created by PDUs sent from the ship VDE. He is given only an out-of-the-window view from his tank. (2) The tank's movements are transmitted back as DIS Entity-State data via PDUs and are displayed within the ship VDE. The rest of the design team has freedom to view the scenario from any and multiple design perspectives. (3) Both the tank and the NBS are virtual prototypes created in their own separate SDE but joined together in this simulation. As the tank driver maneuvers his vehicle, any fouls between the tank and the ship are automatically flagged and recorded for the entire design team to evaluate.

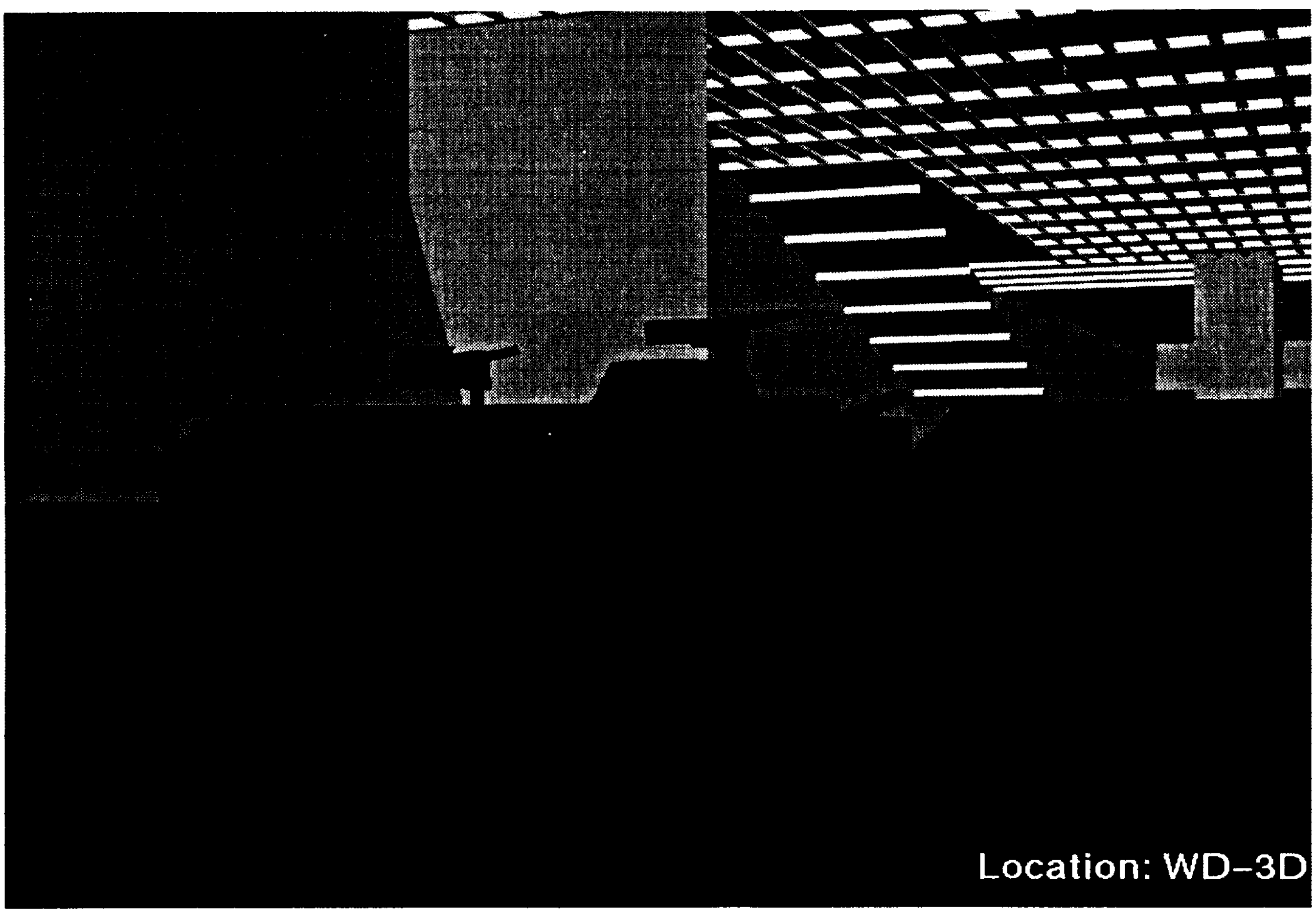

Figure 18 - Tank simulation is linked to the NBS in SBD's Virtual Design Environment.

MULTI-DISCIPLINARY ANALYSES

In this segment, complex engineering analyses necessitated by the design changes are planned and executed. Due to the increase in ship top speed (new engine), together with the weight and structural arrangement changes, a new computation of dynamic loads resulting from ship response in the seaway is required. Using visual programming tools, an analysis procedure is set up that uses hydrodynamic codes, coupled to linear ship response codes, to compute ship motion for a range of ship speed, heading and sea states. As shown in Fig. 19, the resulting ship motion is displayed, using VDE and the viewer sees the NBS traversing a stressing seaway condition. From examination of these results, the ship responses are judged to be too large to base reliable load predictions on linear theories. A separate nonlinear analysis of critical conditions is then set up and routed to a remote supercomputing facility to be executed. External loads from this analysis are transferred to a FEM of the NBS and internal loads are computed. Again using VDE, members of the design team immerse themselves within the ship to examine stress concentrations in areas of the design changes. This examination reveals excessive stress in the deck, leading the structural analyst to decrease stiffener spacing via the VDE to solve the problem.

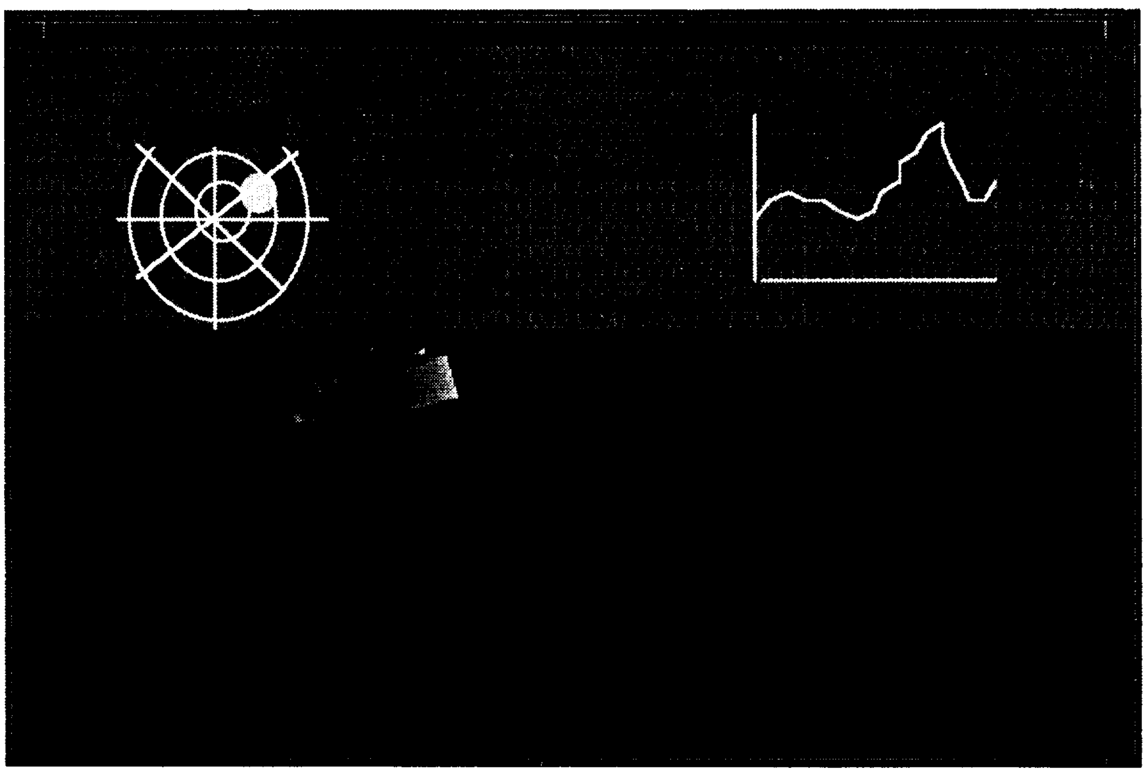

Figure 19 - Ship's motion and dynamic loads are viewed in SBD's Virtual Design Environment.

MANUFACTURING ANALYSIS

Notified of all the design changes made in the previous segments, a Manufacturing Specialist invokes his model of the manufacturing processes required to construct the NBS. As indicated in Fig. 20, all design change data are automatically incorporated in this analysis through its linkage back to the Smart Product Model. For this exercise, the G2 discrete event simulation package from Gensym is used to model the work flow processes. The segment focuses on simulating activity within the shipyard's steel fabrication facility. Cost estimates of each process are generated and accumulated as the simulation executes. To lower total cost, a process modification (addition of a second blast and coat operation) is made and is found to reduce schedule, inventory costs and, hence, total cost.

- Gensym's G2 discrete event simulation
- Smart Product Model automatically linked updated design, process and cost data / models to simulation

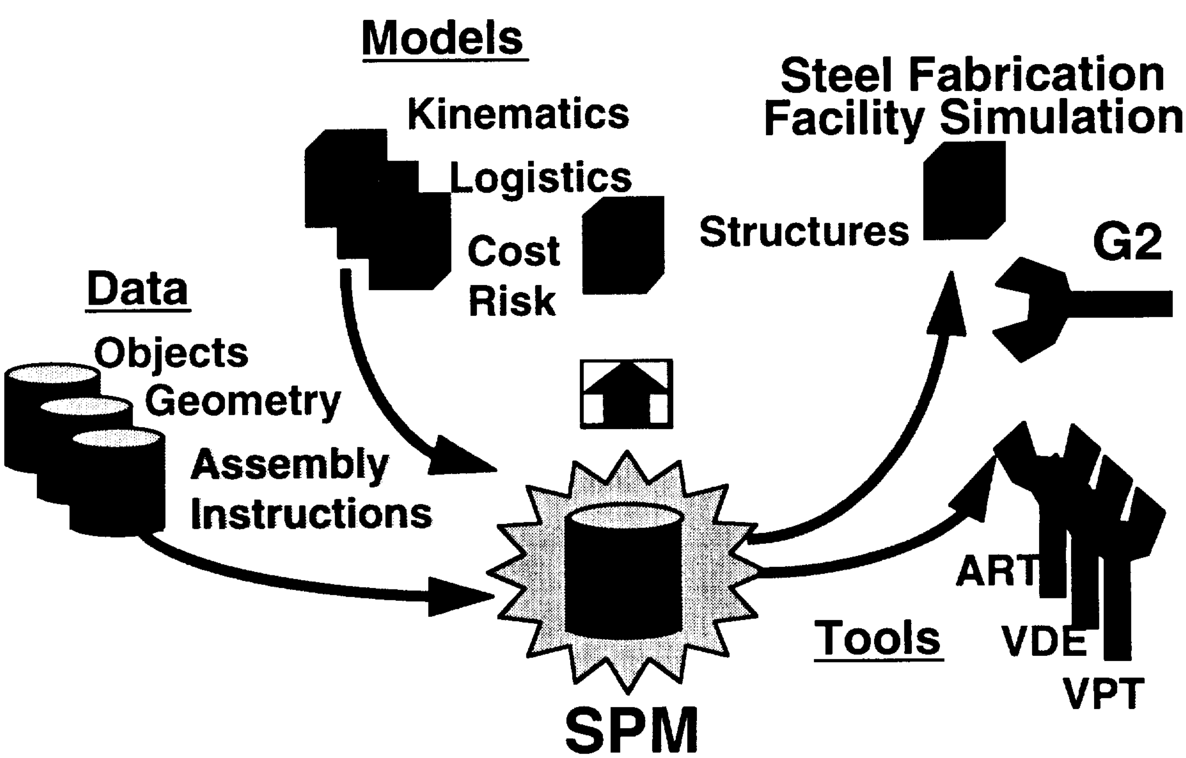

Figure 20 - SBD's Smart Product Model links design changes to manufacturing process simulation.

COST/RISK ANALYSIS

When the scenario originally began, a cost estimate was made using historical data available from the baseline NBS design. During the various segments, as design and process changes were made, data that have a direct bearing on the cost were changed. SBD includes a tool (VPT) that keeps track of the cost impacts of the changes as the design modification progresses. As shown in Fig. 21, VPT provides dynamic costing information, in effect creating a "cost meter" to help identify cost problems as they arise and evaluate solutions as they are proposed.

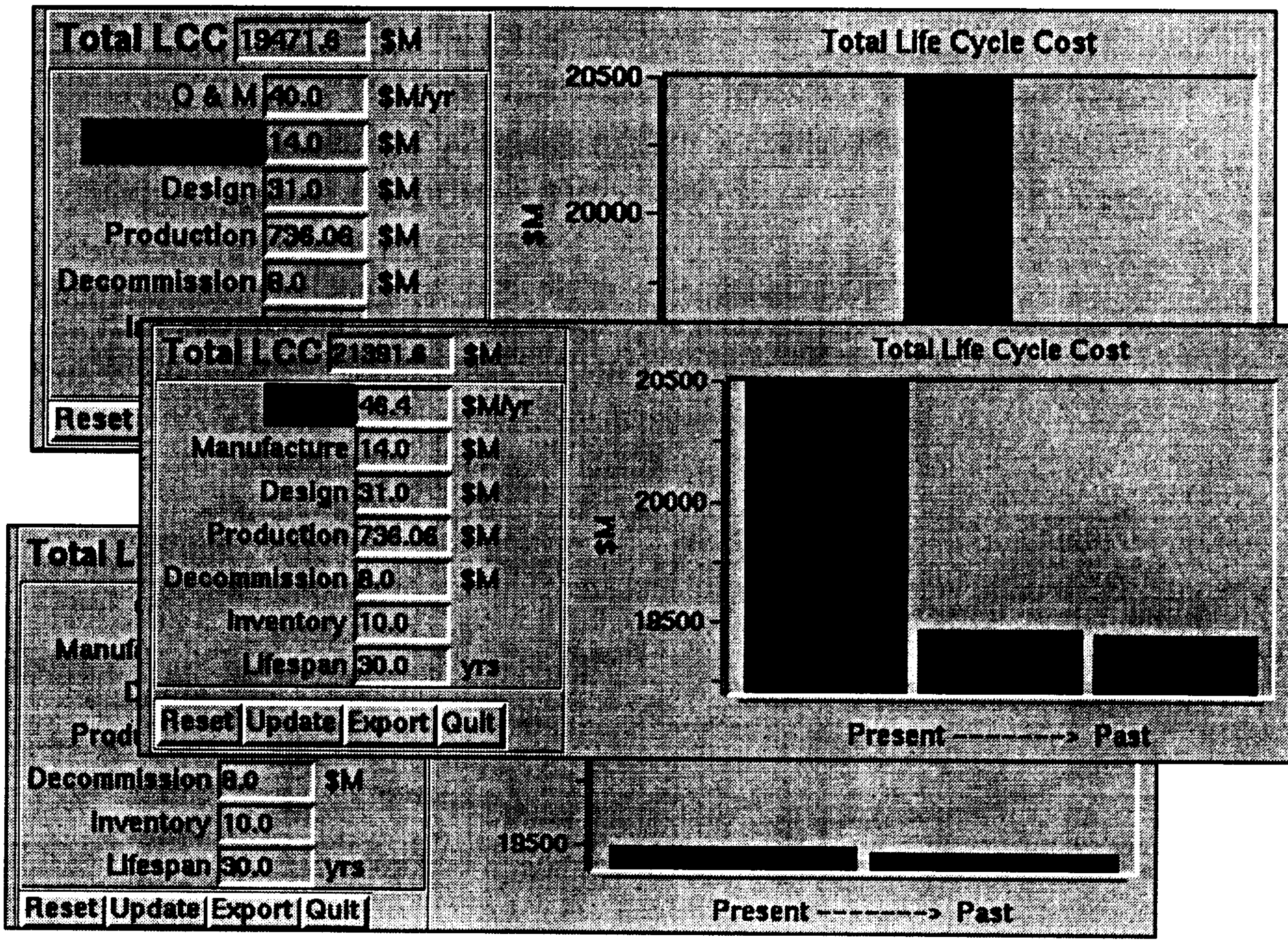

Figure 21 - SBD's Virtual Prototyping Tool (VPT) provides dynamic costing.

COST/RISK ANALYSIS (CONTINUED)

At the end of the design exercise, final cost and risk analyses are performed to definitize the likely impact of the changes, including the ever-present uncertainty in cost estimates. As shown in Fig. 22, these results show that the final refined analysis has less uncertainty in its predicted cost and that the predicted (most likely) cost is similar to the original estimate. Thus, these analyses produce results that confirm the correctness of the original decision to modify the design to increase ship top speed, rather than simply increasing the production run.

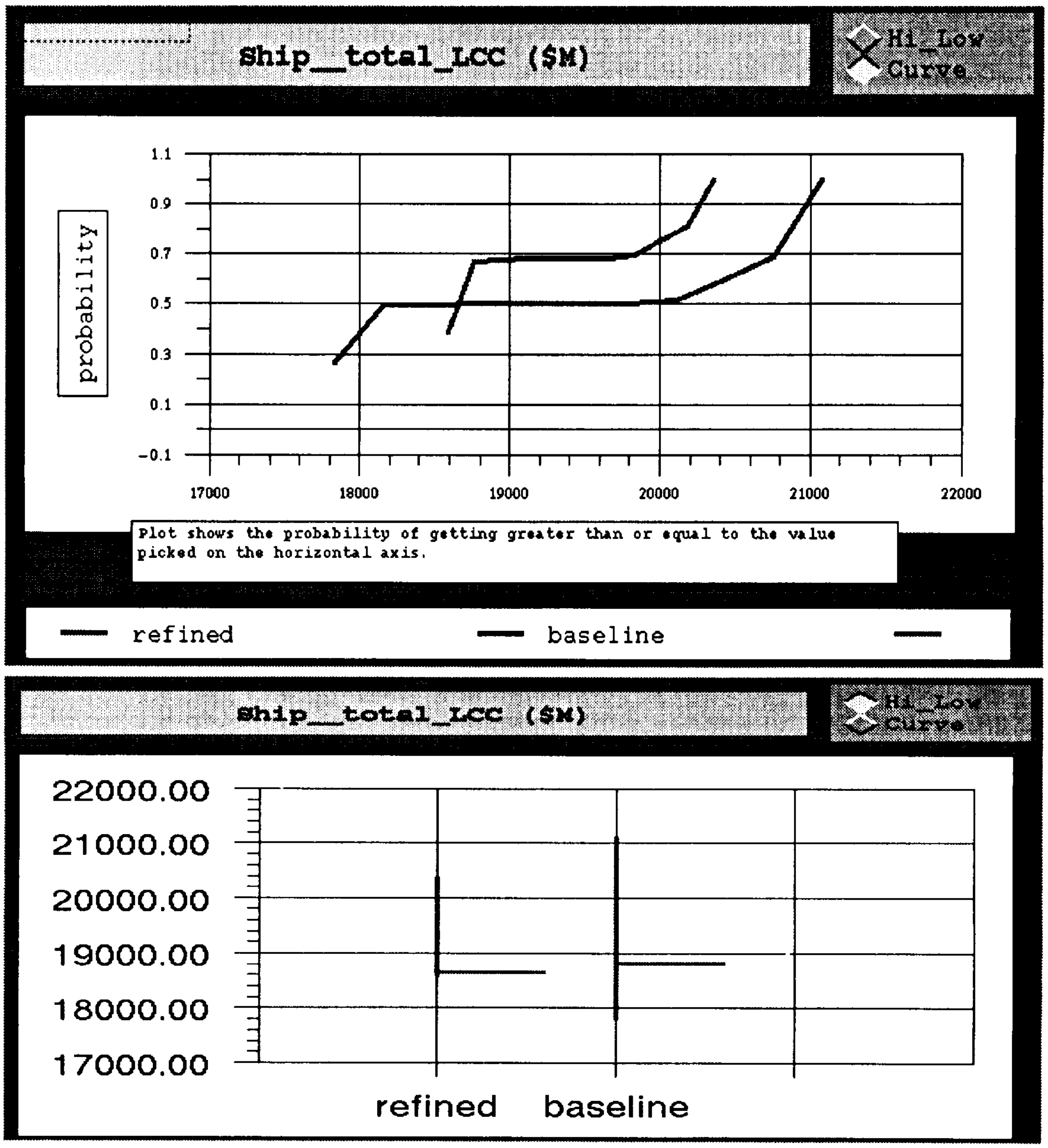

Figure 22 - SBD's VPT computes uncertainty in basic design metrics such as cost.

CONCLUSION

The series of analyses and design activity performed in the demonstration scenario were representative of a set of activities necessary to perform the required design study. While the demonstration took approximately three hours to complete, performance of a similar scope activity without SBD technology was estimated to require two months -- a two-order-of-magnitude difference. As indicated in Fig. 23 below, the SBD demonstration convinces us that practical, powerful virtual design environments are feasible today.

- **Shipbuilding demonstration showed a two-order of magnitude improvement in design cycle response time**
- **SBD demonstration showed that a powerful VDE is feasible <u>today</u>**
- **Necessary technologies are available and improving rapidly**
- **Future advanced immersive environments will lower cost and improve realism**
- **Development of a prototype, general-purpose virtual design environment (i.e., SBD) is timely**

Figure 23 - Conclusions of SBD demonstration.

SUMMARY

Figure 24 summarizes this paper. Advances in computer hardware, computer software and computer science have provided the tools needed to revolutionize the traditional product development cycle. The evolution of computer aided design has reached the age of synthetic design environments, in which computer-generated virtual prototypes of complex systems will be the central unifying basis for all product development activities. Design, engineering, manufacture planning, product test, and operator training will all be performed with virtual prototypes in synthetic design environments (SDE).

To demonstrate the feasiblity of this bold concept, a notional SDE was constructed for the ship building industry. Denoted as the Simulation Based Design (SBD) environment, this SDE was used to conduct a demonstration ship design scenario. Starting from the definition of mission requirements and following into design, engineering and manufacture planning, this demonstration used many advanced technologies to show how an SDE might operate and to quantify the improvement that it could produce in the design cycle of a product as complex as a modern ship.

The integration of the technologies embodied in SBD was shown to lead to a large (two orders of magnitude) productivity increase in the product development process. Central ingredients of SBD were the immersive design visualization environment, the "smart" product model, the integrated cost and risk tool, and the visual programming environment. SBD offered a rich human-computer interface to create a design space in which a team of engineers and designers viewed and interrogated the product as they designed and analyzed it. The precise nature and quality of the human-computer interface provided by future synthetic design environments will determine their acceptance, utility and, ultimately, the extent of true productivity gains.

- **Advances in computer technology and computer science are revolutionizing the design process**
- **Next step in evolution of computer aided design is the Synthetic Design Environment (SDE)**
- **An SDE, known as Simulation Based Design (SBD), was demonstrated for shipbuilding**
  - **Immersive visualization**
  - **Smart product model**
  - **Integrated cost and risk assessment**
  - **Visual programming environment**
- **Acceleration of design process by two orders of magnitude is possible**

Figure 24 - Summary of the demonstration of a synthetic design environment for shipbuilding.