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What is Set-Based Design?

ABSTRACT

On February 4, 2008 Admiral Paul Sullivan, Commander of the Naval Sea Systems Command, sent out a letter entitled: Ship Design and Analysis Tool Goals. The purpose of the widely distributed memorandum was to state the requirements and high-level capability goals for NAVSEA design synthesis and analysis tools. In this memo, Admiral Sullivan expressed the need for evolving models and analysis tools to be compatible with, among other things, Set-Based Design (SBD). Admiral Sullivan's memo was a major step towards improving ship design programs with new, more powerful analytical support tools but many have asked, "What is Set-Based Design and how does it relate to Naval Ship Design"?

SBD is a complex design method that requires a shift in how one thinks about and manages design. The set-based design paradigm can replace point based design construction with design discovery; it allows more of the design effort to proceed concurrently and defers detailed specifications until tradeoffs are more fully understood. This paper describes the principles of SBD, citing improvements in design practice that have set the stage for SBD, and relating these principles current Navy ship design issues.

INTRODUCTION

Traditional design process or methods have often failed due to the inherent complexity of large-scale product design. The push to exclude the human in design through automation has left a void. Many optimization codes, expert systems, and synthesis loops cannot capture the depth or intent of a human designer. Designing large complex systems, such as naval vessels, requires human involvement but the increased complexity of these vessels also requires a new approach to design.

Advanced design in the United States has begun to emphasize the use of a multidisciplinary team-based concurrent engineering approach, with notable successes in the automotive (Chrysler Viper, Ford Mustang) and aircraft industries (Boeing 777). Integrated Product Teams (IPT's) have also been advocated for future naval ship design (Keane and Tibbitts 1996, Bennett and Lamb 1996, Fireman et al. 1998). During the LPD17 design core cross-functional design teams were co-located or linked in a virtual environment to perform the overall design task. The designer members of a cross-functional team are able to comprehend, process, and negotiate the complex range of issues and constraints relevant to a particular design.

Keane et al (2006) discuss the critical need for a collaborative product development environment to provide a solution to some of the Navy's critical cost and future design issues. Recently a Global Shipbuilding Industrial Base Benchmarking Study (May 2005) was completed. This is a comprehensive study that concluded that the major areas of research needed to make the construction of Naval vessels cost competitive are in the areas of design, engineering, and production engineering. Current analysis of the country's ability to design and build the next generation of vessels has also shown that there is a serious shortage of engineers and a loss of critical skills due to attrition in the experienced design community. The result is that younger, less experienced engineers have been given the role of ship design manager where in the past older, more practiced engineers had typically been used to fill this role. Because of this, new methods for design communication, negotiation, and information transfer are needed to augment the experience of the younger ship design managers. This transition to younger designers is an opportunity to change the way in which the

Navy designs vessels. Set-Based design is one such opportunity.

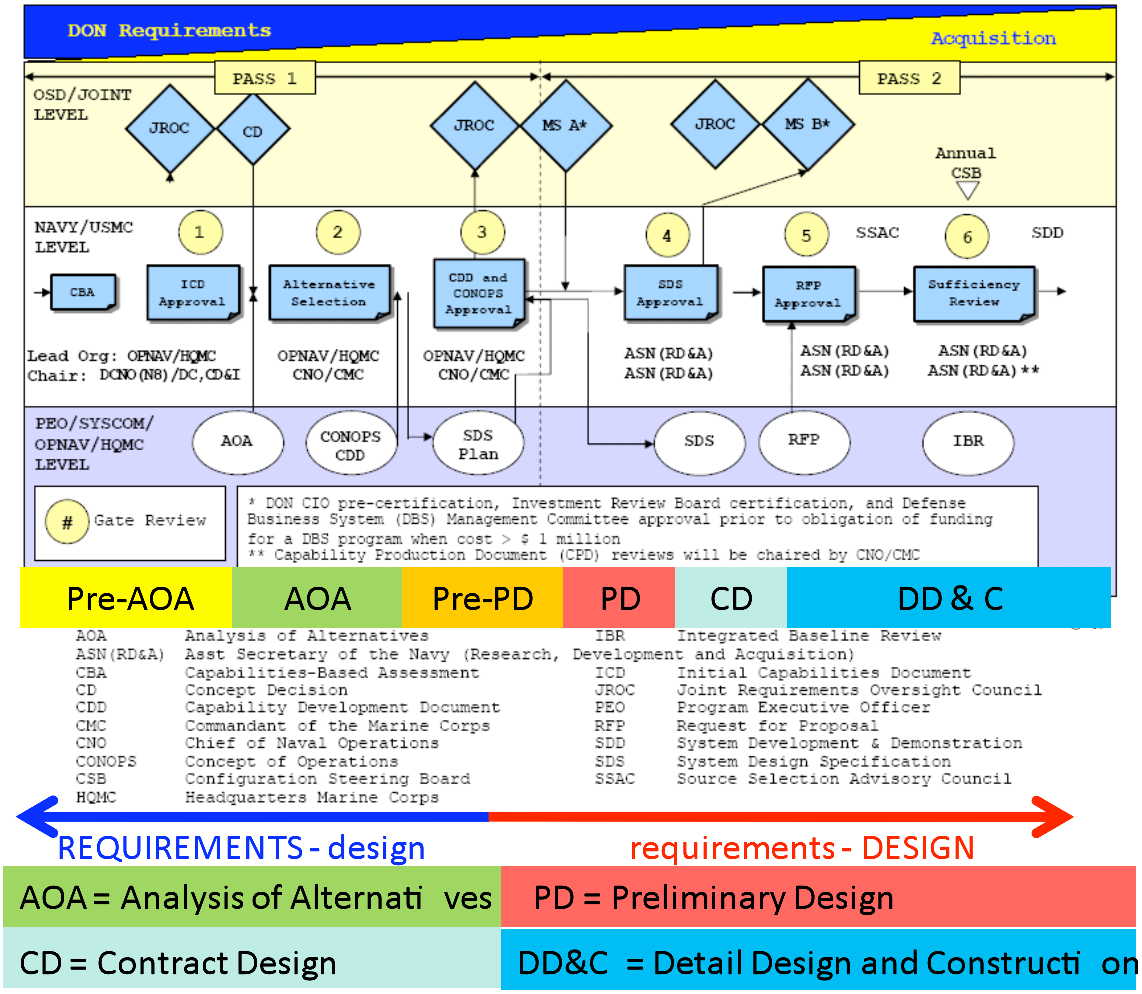
NAVY INTEREST IN SET BASED DESIGN

During 2008, the Secretary of the Navy (SECNAV) implemented a modified acquisition process as shown in Figure 1. This "2 Pass – 6 Gate" process ensures that the appropriate stakeholders are involved in acquisition decisions from the development of the Initial Capabilities Document (ICD) through Detail Design and construction. (SECNAV 2008a and 20008b) Figure 1 also shows the mapping of the traditional ship design stages onto the new process. Of particular note is the Pre-Preliminary Design phase between the completion of the Analysis of Alternatives (AOA) and Preliminary Design following Milestone A. Set Based Design is anticipated to have the greatest benefit to the Navy during this phase.

Previously, the desired outcome of an independently conducted AOA was a preferred alternative, or point design, that would become the basis for Preliminary Design. During the past few years however, AOAs for LHA(R), MPFF, and CG(X) have not produced a preferred alternative that the Navy has then proceeded to produce. For LHA(R) and MPFF, the final acquisition alternative implemented (after much delay) was not part of the recommended solution set coming out of the AOA (Warner 2005, 2006). For CG(X), the final acquisition alternative has not been selected a year after the originally scheduled completion of the AOA. (O'Rourke 2008) At best, the AOAs have managed to identify a range of possible solutions for a range of desired capabilities. It has been left to the Navy to further refine the requirements and the solution before the commencement of Preliminary Design. The new "2 Pass – 6 Gate" process recognizes that this Pre-Preliminary Design is needed between Gates 2 and 3.

Pre-Preliminary Design is a unique opportunity to perform trade-offs among individual system performance, total ship performance / requirements, the Concept of Operation (CONOPS) and cost. Because these activities are typically performed by many geographically dispersed organizations, Set-Based Design techniques are ideally suited for communicating individual design solution opportunities and requirements to systematically neck down the design space while improving design fidelity. By the end of Pre-Preliminary Design, the requirements are fixed in a Capability Development Document (CDD) and the Concept of Operation formalized in a CONOPS document. The ship design is developed to the level of detail necessary to produce a budget quality cost estimate. The Ship-to-Shore Connector (SSC) design is a good recent example of using Set-Based Design.

At the start of Preliminary Design following a Milestone A decision, in traditional practice, the requirements and CONOPS for the ship are largely fixed. While change is still possible, large changes are generally avoided. Set-Based Design practice offers considerable flexibility for continued system refinement and integration into a total ship design. At some point, the design will "converge" and point design methods are then typically used to modify the design in response to detailed analysis, obsolescence management, and optimization efforts.



AOA	Analysis of Alternatives	IBR	Integrated Baseline Review
ASN(RD&A)	Asst Secretary of the Navy (Research, Development and Acquisition)		
CBA	Capabilities-Based Assessment	ICD	Initial Capabilities Document
CD	Concept Decision	JROC	Joint Requirements Oversight Council
CDD	Capability Development Document	PEO	Program Executive Officer
CMC	Commandant of the Marine Corps	RFP	Request for Proposal
CNO	Chief of Naval Operations	SDD	System Development & Demonstration
CONOPS	Concept of Operations	SDS	System Design Specification
CSB	Configuration Steering Board	SSAC	Source Selection Advisory Council
HQMC	Headquarters Marine Corps		

Figure 1: Navy Acquisition 2 Pass 6 Gate Acquisition Process and Stages of Design. (SECNAV 2008)

DESIGN METHODS THEORY DISCUSSION

The traditional approach to communicating the initial ship design process is the “design spiral” (Evans 1959). This model emphasizes that the many design issues of resistance, weight, volume, stability, trim, etc, interact; and these can be considered in sequence, in increasing detail in each pass around the spiral, until a single design which satisfies all constraints and balances all considerations is reached. This approach to design can be classed as a point-based design since each iteration attempts to develop a design that meets the requirements. The result is a base design that can be developed further or used as the starting point for various tradeoff studies. A disadvantage of this approach is that while it produces a feasible design it will typically not produce a global optimum. Another disadvantage is that the number of iterations around the spiral is generally limited by the available time and budget. There is a tendency to declare the design complete at the end of the scheduled time period, whether or not the design has converged..

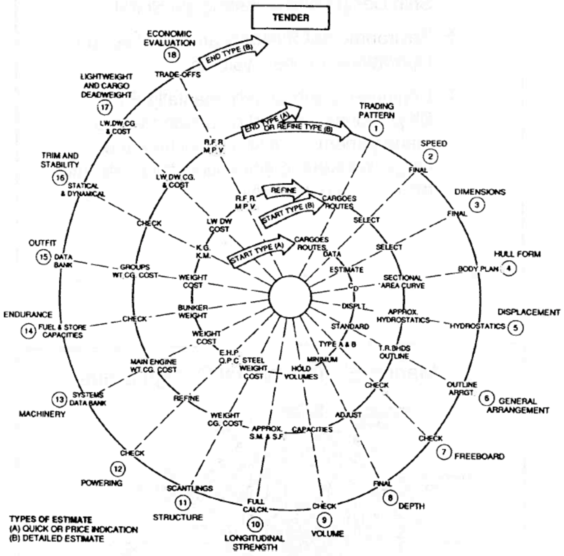


Figure 2: Classical Design Spiral. (Evans 1959)

In general, point-based strategies consist of five basic steps (Liker et al 1996)

1. First, the problem is defined.
2. Engineers generate a large number of alternative design concepts, usually through individual or group brainstorming sessions.
3. Engineers conduct preliminary analyses on the alternatives, leading to the selection of a single concept for further development.
4. The selected concept is further analyzed and modified until all of the product's goals and requirements are met.
5. If the selected concept fails to meet the stated goals, the process begins again, either from step 1 or 2, until a solution is found.

One step beyond point-based design is concurrent engineering (CE). In CE the point based design approach is still implemented but engineers analyze in parallel a specific design based on a request for analysis. The major improvement CE has brought to the engineering community is enhanced communication enabled by collocation. Collocation shortens the design processes and mitigates the errors due to limited intra-team communication caused by distance. CE is a widely researched and implemented concept. As designs have become more complex, CE has been more frequently used. While CE approaches have improved the design of complex systems, it has not changed the fundamental point design process. Prior to CE most designs where completed with an "over the wall" approach. CE has simply "lowered the wall." (Bernstein 1998).

The design and production of automobiles by Toyota is generally considered world-class, and as such, it has been, subjected to considerable study. The study of the Toyota production system led to the conceptualization of Lean Manufacturing (Womack et al. 1990). The Japanese Technology Management Program sponsored by the Air Force Office of Scientific Research at the University of Michigan subsequently studied the Toyota approach to automobile design (Ward et al. 1995a, b). The Toyota processes produce world-class designs in a significantly shorter time than other automobile manufacturers. The main features of this design process include:

1. broad sets of design parameters are defined to allow concurrent design to begin,
2. these sets are kept open longer than typical to more fully define tradeoff information,
3. the sets are gradually narrowed until a more globally optimum solution is revealed and refined.
4. As the sets narrow, the level of detail (or design fidelity) increases

This approach is illustrated in a sketch produced by a Toyota manager in Figure 3. Alan Ward characterized this design approach as set-based design. It differs from point-based design where critical interfaces are defined by precise specifications early in the design so that sub-system development can proceed. Often these interfaces must be defined, and thus constrained, long before the needed tradeoff information is available, inevitably resulting in a sub-optimal overall design.

For example, consider the competition for volume under dashboard that might arise between an audio system and a heating system. Rather than specify in advance the envelope into which each vendor's design must fit, they can each design a range of options within broad sets so that the design team can see the differences in performance and cost that might result in tradeoffs in volume and shape between these two competing items.

Table 1, based significantly on Bernstein (1998), compares set-based design to point based design.

The set-based design approach has a parallel in the Method of Controlled Convergence (MCC) conceptual design approach advocated by Stuart Pugh (1991) and design-build-test cycle (DBT) advocated by Wheelwright and Clark (1992).

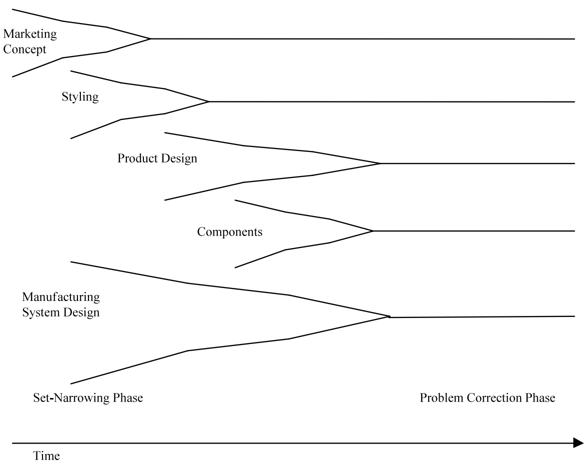


Figure 3: Parallel Set Narrowing Process Sketched by a Toyota Manager. (Ward 1995b)

In MCC, engineers develop a large number of total designs, and once created, they are evaluated against requirements. The designs that meet the requirements and are Pareto Optimal are kept. Those designs that do not meet the requirements or are Pareto Dominated are either discarded or modified. This is repeated as the set of designs is reduced. Additional alternatives, modifications to remaining designs, or modifications of discarded designs (to preserve desirable attributes that would otherwise be discarded) can be introduced during each cycle but the number of designs should decrease over time. This continues until only one design remains. and is symbolically shown in the figure below (Bernstein 1998).

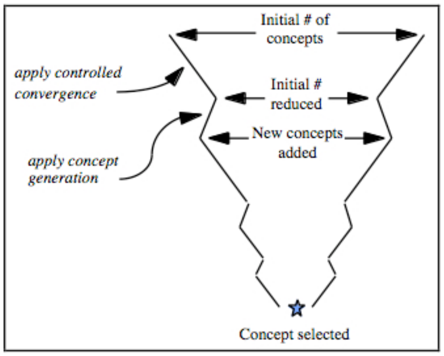


Figure 4: Method of Controlled Convergence. (Bernstein 1998)

The Design-Build-Test Cycle approach is a repetitive iterative approach based on designing concepts, testing concepts, and improving concepts based on testing. The DBT process is shown below.

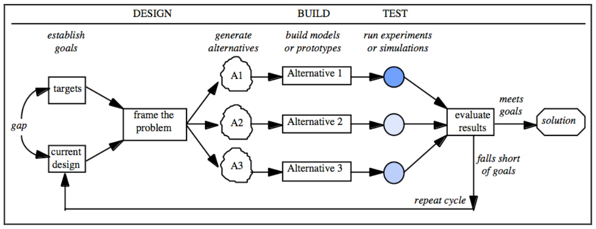


Figure 5: The design-build-test cycle. (Bernstein 1998)

It is obvious that SBD, MCC and DBT are similar but how are they different? All three methods are centered on the idea of multiple alternatives but they differ on how the alternatives are used. In MCC and DBT alternatives are created and evaluated to better understand how different design parameters, or configurations, impact the concepts ability to satisfy a user requirement. SBD uses the generated options in this manner as well but "set-based methods also use options to allow each specialty group working on a product to explore the design space independently. By allowing specialty groups to independently analyze their design options, set-based methods eliminate the iterative paths that can be so problematic in point-based approaches.

Controlled convergence and design-build-test do not necessarily emphasize this use of design options." (Bernstein 1998)

Table 1: Comparison of Point Based Design and Set Based Design. (Based on Bernstein 1998)

Task	Point Based Design	Set Based Design
Search: How to find solutions.	Iterate an existing idea by modifying it to achieve objectives and improve performance. Brainstorm new ideas	Define a feasible design space, then constrict it by removing regions where solutions are proven to be inferior
Communication: Which ideas are communicated	Communicate the best idea.	Communicate sets of possibilities that are not Pareto dominated.
Integration: How to integrate the system	Provide teams design budgets and constraints. If a team can't meet budget or constraints, reallocate to other teams	Look for intersections that meet total system requirements.
Selection: How to identify best idea.	Formal schemes for selecting the best alternative. Simulate or make prototypes to confirm that the solution works	Design alternatives in parallel. Eliminate those proven inferior to others. Use low cost tests to prove infeasibility or identify Pareto dominance
Optimization: How to optimize the design	Analyze and test the design. Modify the design to achieve objectives and improve performance.	Design alternatives in parallel. Eliminate those proven inferior to others.
Specification: How to constrain others with respect to your subsystem design?	Maximize constraints in specifications to assure functionality and interface fit.	Use minimum control specifications to allow optimization and mutual adjustment.
Decision Risk Control: How to minimize risk of "going down the wrong path?"	Establish feedback channels. Communicate often. Respond quickly to changes.	Establish feasibility before commitment. Pursue options in parallel. Seek solutions robust to physical, market, and design variations.
Risk control: How to minimize damage from unreliable communications; how to control communications	Establish feedback channels. Communicate often. Respond quickly to changes. Review designs and manage information at transition points.	Stay within sets once committed. Manage uncertainty at process gates.

Corporate Culture's Impact on Successful SBD

Toyota's growth and market share make it apparent that, if SBD practices are contributing to their success, the method has merit and should be investigated for potential application in naval ship design. Even though Toyota has shared many details of its manufacturing practices, it has been closed lipped about many of the details of its design process. Many believe that Toyota's design process is one of the major accomplishments that have enabled them to be so successful. Toyota calls its process and culture the "Toyota DNA" and explains it as a cultural difference between their company and others (Liker 2004). In the recent book *The Toyota Product Development System: Integrating People, Process, and Technology,* written by James Morgan and Jeffrey Liker (2006), the authors identify 13 Lean Product Development System Model principles, which are broken down into three mutually supportive aligned subsystem elements, that make up the "Toyota DNA".

A. Process

   1. Establish customer defined value to separate value-added from waste
   2. Front-Load the Product Development Process to Explore Thoroughly Alternative Solutions while there is Maximum design space
   3. Create a Leveled Product Development Process Flow
   4. Utilize Rigorous Standardization to Reduce Variation, and Create Flexible and Predictable Outcomes

B. Skilled People

   5. Develop a Chief Engineer System to Integrate Development from Start to Finish
   6. Organize to Balance Functional Expertise and Cross-Functional Integration
   7. Develop Towering Technical Competence in all Engineers
   8. Fully Integrate Suppliers into the Product Development System

    9. Build in Learning and Continuous Improvement
    10. Build a Culture to Support Excellence and Relentless Improvement
- C. Tools and Technology
    11. Adapt Technology to Fit Your People and Process
    12. Align your Organization through Simple, Visual Communication
    13. Use Powerful Tools for Standardization and Organizational Learning

Of the 13 principles that make up the Toyota Product Development System principle 2, front-Load the product development process to explore thoroughly alternative solutions while there is maximum design space, is the only principle that is uniquely related to SBD. The remaining twelve principles enable Toyota to make the SBD methodology a practical reality.

The U.S. Navy will not be able to create the same culture as Toyota, thus research is needed to create a system that achieves the essential advantages of the Toyota SBD design process. The major obstacle to SBD in Naval design is how to facilitate manage, and implement SBD when the constraints and milestones of current acquisition policies are keyed to point design practice.

WHY IS SBD USEFUL

The value of SBD has been a source of confusion. The manufacturing and design processes of Toyota are, at first glance, counter intuitive. One paradox associated with Toyota is in its Lean Manufacturing System and just-in-time inventory. It is paradoxical because during the 1980's Toyota did not follow traditional manufacturing approaches. Traditional manufacturing practice holds that economy of scale is the best path to better products at lower cost: one minimizes price by maximizing machine speed and capacity while neglecting the impact of space, transportation, and inventory. However, Toyota operated with little to no inventory and manufactured vehicles at a lower cost with better quality. A second paradox is described in the article: *The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster* (Ward et al 1995b). This article describes the concept of SBD and demonstrates how even though Toyota severely delays critical design decisions when compared to other auto manufacturers, their time to market is shorter than the competition. The reason for delaying decisions has to do with cost, knowledge, and influence. A few of the reasons why SBD is successful follow.

When engineers look at the cost of a project most try to predict the final cost of a product and match that to a budget. One issue a design program has is that the program does not incur major portions of the total cost of the product until very late in the development cycle while the program committed to these costs very early in the program. SBD strives to reduce the Committed Costs to more closely follow the Incurred Costs.

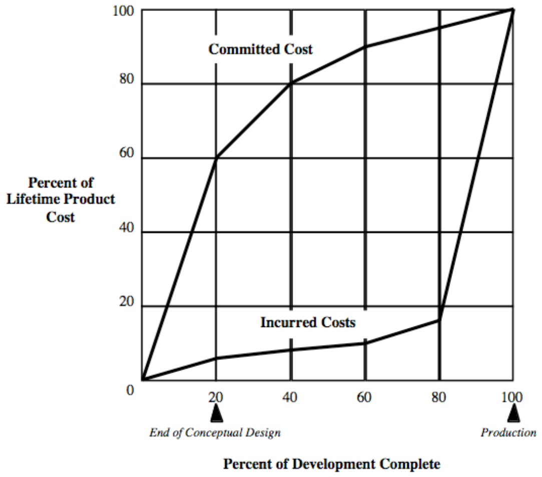


Figure 5: Designing-in costs. (Bernstein 1998)

The second area that SBD has impact on is knowledge. In any design, knowledge increases over time. Early in the design process engineers, managers and the customer know very little due to the fact that the details concerning the design are neither well defined, developed, or understood. Consequently, decisions during the early stages of product development are made with incomplete data. As the design evolves over time the engineers, managers and customer better understand, due to analysis and experience, the product and the requirements that are driving the product design.

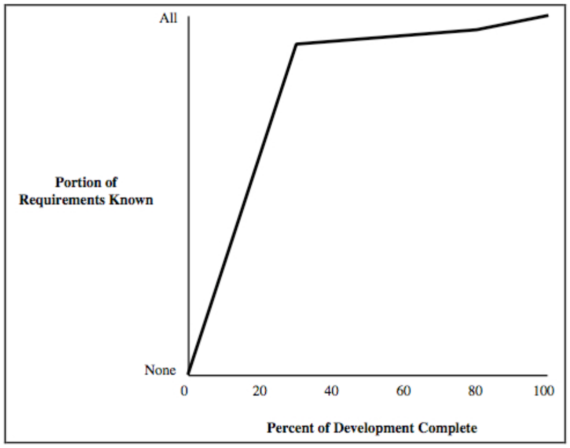


Figure 6: Evolution of design knowledge. (Bernstein 1998)

A third area that SBD has impact is stakeholder influence. All stakeholders have the greatest impact on any design during the initial stages of the design process. At this stage, the design and its requirements are a blank canvas and any decision made obviously has an impact on the final product performance and cost. As the design matures, stakeholders' ability to impact the design diminishes because the design becomes more locked in (as represented by the Committed Cost curve) and any major change, cost prohibitive.

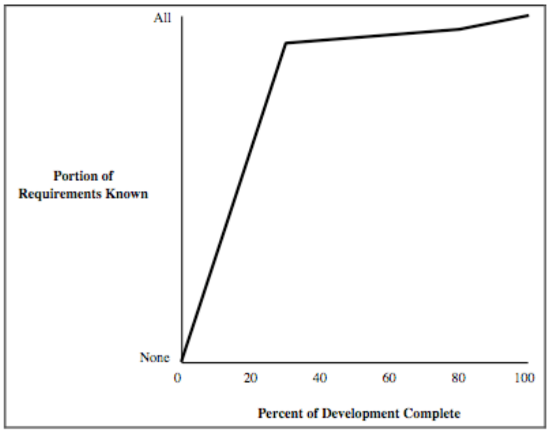


Figure 7: Evolution of design knowledge. (Bernstein 1998)

As stated earlier, the goal underpinning the use of SBD is the delay of critical decisions to the latest point possible. By delaying decisions, one can improve the design by delaying the commitment of cost until later in the design process and until such time that our information is much better. By delaying the cost commitment we also increase the time in which stakeholders can influence a design. This can be seen in figure 8.

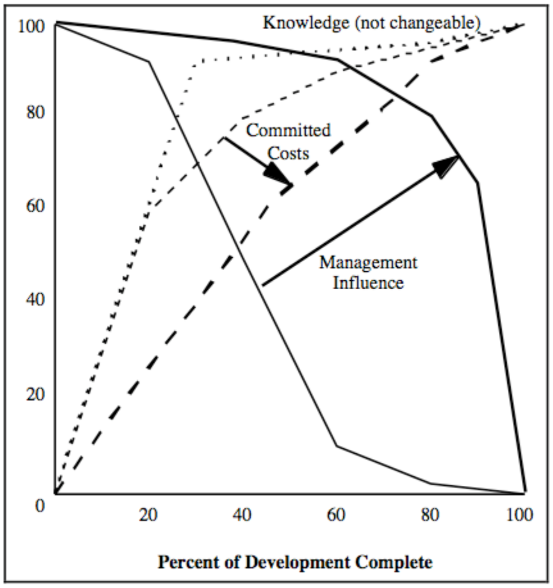


Figure 8: Impact of SBD of the design process. (Bernstein 1998)

CAN SBD BE USED IN SHIP DESIGN?

From 1998 to 2003, the University of Michigan Department of Naval Architecture and Marine Engineering, completed a series of research projects to determine if SBD could be used to successfully design a ship. The research focused on how to get a group of designers, described as human design agents, to communicate in a way that would foster SBD and compare that to traditional collaborative and non-collaborative design experiences.

The first group of experiments used the Responsible Agents for Product/Process Integrated Development (RAPPID) product, developed by The Center for Electronic

Commerce of the Environmental Research Institute of Michigan (ERIM). RAPPID facilitated negotiation between the human agents to foster SBD and was designed to help human designers manage product characteristics across different functions and stages in the product life cycle (Parunak et al 1998, 1999a, b).

The RAPPID experiments showed that a hybrid system of human design agents and intermediate computer agents exhibited promise as a means of achieving effective conceptual ship design by a cross-functional design team (Parsons et al 1999). It fostered a set-based design approach to conceptual ship design. The following specific conclusions were noted:

- The negotiation across the network provides an effective way to balance the interests of the design team members.
- A converged marketplace can assess the interaction and design value of different parameters even in the absence of analytical theories.
- The process is robust to intermediate design errors. During the experiment, the logic used by the student agents to set block coefficient was incorrect for about half of the design period. When this was discovered and corrected, the sets were still wide enough that the process was able to move forward and reach a converged solution without major rework. In a point-based design approach the team would need to start the design over.
- The recorded market histories permit design logic capture and institutional learning.
- The RAPPID market approach proved difficult for the naval architects to apply, and the RAPPID interface allowed only one-on-one negotiation even though many agents had critical interests in some parameters.
- The hybrid agent approach can provide a means to address the potentially limiting design communication and negotiation process in advanced cross-functional team design, even if it is virtually linked across the Internet.

To validate the hybrid agent model team approach, a nonlinear optimization program (NLP) was created using the same basic equations as the hybrid agent model as well as the same requirements. The optimal preliminary container ship design was completed as part of a professional degree thesis at the University of Michigan (Skwarek 1999)). The results of the NLP showed that the hybrid agent model was capable of producing a design that compared well with a conventional optimization solution. It should be noted that the agent model was capable of handling a larger number of variables and design considerations than typically programmed into NLP solutions.

The second set of experiments used a fuzzy logic based communication system (Parsons and Singer 2000, Singer and Parsons 2003). The conclusions made from the experimental series are that the fuzzy logic agent software does facilitate set-based design, thus, increasing the probability of reaching a more globally optimal ship design. The set-based design paradigm can replace point based design construction with design discovery; it allows more of design to proceed concurrently and defers detailed specifications until tradeoffs are more fully understood.

One of the underlining advantages of the fuzzy logic agent software is its ability to keep the variable sets open longer, which will, in theory, facilitate and enable set-based design. In open form communication there are no controls to assure that all team players are actively participating in the set-based design philosophy. The fuzzy agent software eliminated this problem. Since the fuzzy agent software is constantly evaluating the joint preference curves of a variable over the variable's current range, the software possesses the ability to dynamically adapt to the changing design. The software environment also demands and balances the active participation of all agents. The un-balanced participation of engineers is a problem in CE and point-based design programs.

The conclusion from all this research is that SBD can work within a ship design context. In an academic environment SBD produced better solutions faster when compared to optimization methods, non-collocated engineering teams, and point-based design approaches.

HOW TO DO SBD IN GENERAL TERMS

To execute SBD, as with any process, there can be an almost innumerable number of ways to get to the end point. One very powerful way to set course is to posit what should happen if SBD works as intended, i.e., imagine where one would be in the design space at the end of the SBD effort.

First, one would expect to have identified a manageable set of design parameters that have been determined to be principal factors in achieving maximum design value. Next, one would expect to have determined which of the set is more important than the others. One would expect to have identified which design attributes and measures are most important in differentiating among the most promising design combinations. One would also expect to be able comparatively evaluate the most promising designs in an analysis framework that capitalizes on the current best knowledge of design parameters and system attributes to assess total value. One would also expect to be able to examine the impact of changes in attribute preferences on the best design recommendation. Finally, one would expect to have a body of documented trade space analyses that substantiates all discarded or screened design solutions. And, perhaps most important from an SBD objectives viewpoint, this information would be available as a resource for design flexibility in the event of future changes in operational requirements, technology projections, program budgets and other changes in the design environment.

Like most things, in theory the key steps of Set Based Design are few but the subtleties of execution can be many and complex. The three principle concepts to implement SBD are (1) consider a large number of design alternatives by understanding the design space, (2) allow specialists to consider a design from their own perspective, and (3) use the intersection between individual sets to optimize a design and establish feasibility before commitment. (Bernstein 1998). The optimization process can consider physical performance of the design, as well as other attributes such as producibility and acquisition complexity.

One of the major advantages of SBD is that the SBD process makes one truly understand the design space. To understand the design space requires one to first define the feasible regions of the space. This can be either a feasible variable range, such as length or speed, or discrete states of design such as electric drive or traditional gear driven vessel. Once the feasible regions are established the different specialties need to explore tradeoffs by designing/ evaluating multiple alternatives within their domain. As the engineers explore the design alternatives they need to communicate the sets of possibilities back to the other team members and the Design Integration Manager (DIM).

As each group of specialists begins to develop solutions to their area of development responsibility each team needs to integrate each of their designs into the larger context. To "integrate by intersection" the DIM leads the engineering team in identifying intersections of feasible sets between each group. This requires prior agreement of the minimum and maximum bounds of each set. Specialists cannot extend beyond those bounds unless no other options remain. For example, the proposed solutions may involve a single scalable architecture, discrete sets of architectures or solutions wherein each is applicable for a different subset of the range between the bounds.

The ultimate goal of the integration process is a smaller set of unified global concepts created by integrating the sets of designs completed by different functional groups. The integration process is facilitated by conceptual robustness. Conceptual robustness is achieved when engineering decisions concerning one aspect of a design remain valid in the face of design decisions made in other aspects of the design.

One of the most interesting aspects of SBD is how designs evolve over time. Engineers in a

SBD environment are required to increase the fidelity of their options as the design timeline progresses. This ensures that we reduce the set of options based on additional information and not on arbitrary decisions. Convergence of the end product is more likely because decisions are systematically made with an ever-increasing amount of knowledge and detail. The SBD process is depicted in the figure 10.

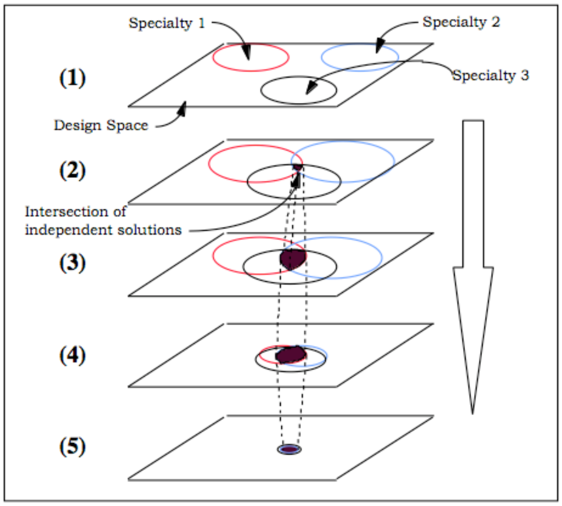


Figure 10: Set-Based Design process. (Bernstein 1998)

CONCLUSIONS

This paper presents the Set-Based Design concept as one that can play an important role in ship design, especially during the critical early stages of design where costs are committed at a much higher rate than costs are incurred. The basic tenets of SBD are

(1) Consider a large number of design alternative by understanding the design space,

(2) Allow specialists to consider a design from their own perspective and use the intersection between individual sets to optimize a design and

(3) Establish feasibility before commitment

Establishing feasibility is achieved by three concepts;

(1) Narrowing sets gradually while increasing detail,

(2) Staying within a set once committed and

(3) Maintaining control by managing uncertainty at process gates.

Applying these principles in a Set-Based Design effort (1) enables the development of conceptually robust concepts and (2) promises a capacity to adapt quickly to changing requirements and design discoveries. Every ship designer should be familiar with this powerful method.

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