Modelling and Simulation Tools for Set-Based Design

Dr. Norbert Doerry

Naval Sea Systems Command

SUMMARY

Set-Based Design (SBD) can be thought of as design by elimination. One systematically decides the regions of the possible design space that are NOT the answer, and then analyzes in more detail the remaining design space to see what additional area of the design space can be eliminated. Ideally, the remaining possible design space will shrink as the amount of detail required to support the next design space contraction decision increases (resulting in roughly the same amount of design work per "iteration"). Eventually a feasible design space emerges from which a low risk solution can be selected.

SBD contrasts with the more traditional iterative point design approaches comprised of initially picking a proposed solution and marginally modifying it when more detailed analysis reveals problems. Some of the advantages of SBD are that it...

- Supports semi-independent (even geographically dispersed) discipline specific sub-teams to work on their domain of expertise without detailed frequent interactions with other sub-teams.
- Enables making "final" decisions much earlier, even with low fidelity tools. Decisions are only made that can be definitively supported with the tools and data used up to that point.
- Enables design reviews to conclude faster because "Did you consider ....?" type questions from stakeholders can be addressed with specific trade-studies conducted to eliminate that region of the design space.
- Enables quick recovery when requirements change, or a mistake in the analysis is identified.

From a design tool perspective, SBD offers a number of challenges. Many design and analysis tools are optimized for working with a specific design solution, not design regions. Furthermore, visualizing and understanding uncertainty in the products of these tools is key to being able to make sound design space reduction decisions. Tools are needed to help visualize the multi-dimensional design spaces for the purpose of understanding the boundaries of the feasible and infeasible design regions. Tools to assist in determining the ordering of decision decisions in SBD are needed as well as tools to enable focusing on specific sub-sets of design variables without ignoring the impact of the remaining design variables. Additionally, tools to facilitate team negotiations, evaluate variable interactions, assess risk, and manage design and decision data are needed.

1: SET BASED DESIGN

SBD is a design method that works well to transition the results of Synthesis Model based Design Optimization methods to either a final design or to one of the traditional Point Based Design (PBD) methods exemplified by the Classic Design Spiral. As shown in Figure 1, many product designs begin with a thorough exploration of a design space using simple tools generally based on parametric relationships through synthesis model based design optimization. While many thousands of concepts can be created with these methods, the level of uncertainty due to the simplistic models precludes the direct selection of an optimal design. In contrast, PBD methods such as the classic design spiral with its increased levels of modelling detail can result in an optimal design given a good starting design and sufficient time and resources. Unfortunately, the results of synthesis model based design optimization are often not good enough to ensure a quick convergence using the classic design spiral. If the classic design spiral is applied too soon, the design process can struggle to achieve feasibility within the allotted time (and budget) for the design phase. SBD provides a structure to design decision making for large scale complex designs conducted by multiple design teams. SBD offers to bridge the gap between a design space characterized by much uncertainty that is created with synthesis model based methods, and the feasible or nearly feasible design needed to initiate the classic design spiral in a PBD process.

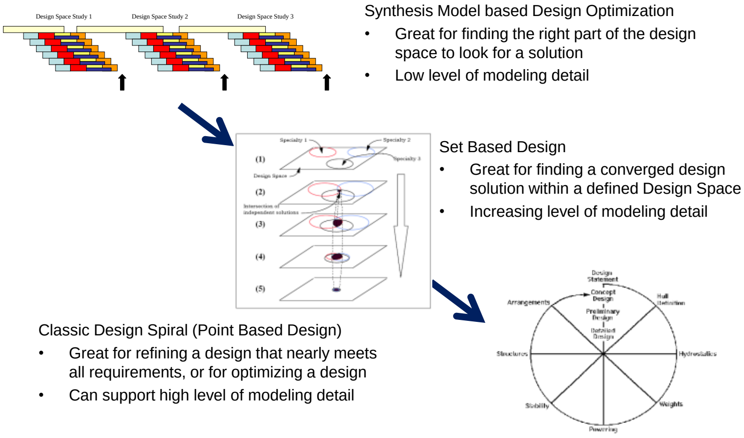

Figure 1: Set Based Design as a transition between design methods

The fundamental principles of SBD are (Singer, Doerry, Buckley 2009):

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

The narrowing of sets in the 3rd principle can be thought of as systematically deciding what is NOT the design solution. Once all of the design space that is not the answer is eliminated, what remains is feasible. A design solution is either directly chosen from the feasible design space, or is established as a good starting point for PBD.

The 4th principle is also very important. Reductions in the design space must be made based on the development of new knowledge. Simply exploring the design space more thoroughly with a low resolution model will not significantly improve the ability to reduce the design space. Ideally, the remaining design space will contract fast enough such that the additional effort required to increase the fidelity of modelling will result in roughly the same amount of time to complete a SBD "iteration".

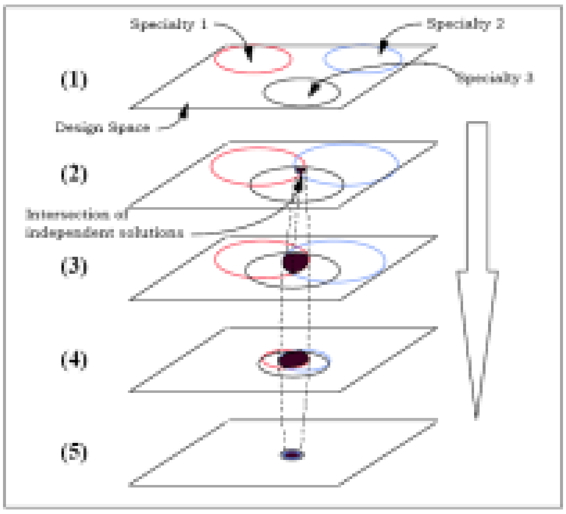

Figure 2: Systematically Constricting Design Space (Bernstein 1998)

SBD is based on the following three tenets (Bernstein 1998):

a. understand the design space,
b. integrate by intersection,
c. establish feasibility before commitment.

SBD contrasts with the more traditional iterative PBD approaches comprised of initially picking a proposed solution and marginally modifying it when more detailed analysis reveals problems. Some of the advantages of SBD are ...

- Each set can be designed by semi-independent (even geographically dispersed) sub-teams without detailed frequent interactions. The design integrator provides each sub-team sets for design input and receives sets of design solutions from the sub-teams. The global solution is integrated by the intersection of the different sets produced by the sub-teams.

- "Final" decisions can be made much earlier, even with low fidelity tools -- it is much easier to show something is not the answer than it is to show something is the best answer. Decisions are only made that can be definitively supported with the tools and data used up to that point.

- PBD often results in a "Pick and Defend" approach that can lead to "Did you consider ....." type questions from stakeholders. The extra work in PBD to address the stakeholder concerns in many cases increases design costs and causes schedule slippage. In SBD, one can usually respond with "yes" and discuss the trade-study that eliminated that region of the design space.

- If requirements change, or a mistake in the analysis is identified, SBD enables one to relatively quickly determine how to recover. In general the design space is expanded to the point just prior to the decisions based on the mistaken analysis or where the requirements impact a decision. (McKenney, Kemink, and Singer 2011). It realize this benefit, tools and methods to record design decisions and the associated design sets are needed.

Mebane et al. (2011) provide a detailed description of how SBD was successfully applied to the design of an air-cushioned vehicle.

2: DESIGN TOOLS FOR SET BASED DESIGN

Since SBD has not yet been widely adopted, supporting design tools are not plentiful. Some challenges with SBD that should be addressed with tools development effort include:

a. Ordering of design decisions

During iterations of SBD, specific trade studies are conducted to enable reduction of the design space. Currently, the focus of design iterations is based on the expertise and experience of the design integrator. Ideally, the design decisions are ordered in such a manner that the largest regions of the design space are eliminated early with the lowest investment of study effort. Generalized process modelling tools, especially those that implement Design Structure Matrices (DSM) can assist in developing the ideal decision order. (Doerry 2009). Decision Oriented Systems Engineering (DOSE) is another method that proved useful in planning the SBD effort for the Navy's Ship to Shore Connector (SSC) design. (Buckley and Stammnitz 2009)

b. Capturing ranges of variables in analysis

Design and analysis tools typically work on point-designs, not on sets. Typically, design space explorations are conducted to categorize the boundaries between competing design strategies. For example, in some portions of the design space, a 450 volt electrical distribution system would be preferred while in other regions a 450 volt system would be infeasible and a 4160 volt electrical distribution system would be preferred. Understanding the location of this boundary in the design space along with the uncertainty is important.

The Computational Research & Engineering Acquisition Tools & Environments (CREATE) program is currently developing a Rapid Design and Integration (RDI) tool that includes the creation and use of response surfaces and behaviour objects to communicate ranges of variables within a design context.

c. Integrating sets to identify infeasible regions in the design space

RDI is also providing an initial capability for the integration of response surfaces form multiple disciplines to identify infeasible regions of the design space as well as suggest updated ranges for the next SBD iteration. Much work still remains to robustly fulfil this task. For now, the integration process is largely a manual process customized for each project.

d. Changing variables of interest

Only a few of the many, many design decisions are addressed during a SBD iteration. The many design decisions not addressed are a source of uncertainty for that iteration. Often, values for these follow-on design decisions are assumed and fixed for the SBD iteration. This is adequate as long as the assumed values do not influence decisions for constricting the sets for the variables of interest. In some cases, the vector of assumed values for the follow-on design decisions can influence the shape of the response surface for the variables of interest. For these cases, it would be appropriate to estimate the magnitude of the uncertainty due to the follow-on design decisions using methods such as Monte-Carlo simulation. A genetic algorithm can also be used to eliminate inferior vectors of assumed values.

e. Visualizing sets / design space

Many visualization tools exist. Most however, require experience and expertise to use correctly and gain insight. A better understanding of how to use these tools is needed to better inform senior leaders and enable better decisions.

f. Facilitate team negotiations, evaluate variable interactions, assess risk, and manage design and decision data

Managing the design process is a key part of SBD. Tools to manage the key aspects of team negotiations, variable interactions, risk assessments, and design and decision data either do not exist or are not optimized for SBD.

3: CONCLUSIONS

SBD is an important technique for the design of complex systems such as naval ships. As a relatively new technique however, design and analysis tools supporting SBD are generally immature.

REFERENCES

Bernstein, J. I., 1998, Design Methods in the Aerospace Industry: Looking for Evidence of Set-Based Practices, Master of Science Thesis, Massachusetts Institute of Technology, 1998.

Buckley, M.E. and Stammnitz, V., 2004, Decision Oriented Systems Engineering (DOSE) A Structured, Systematic Approach to Function Allocation, *Proceedings of the 14th Annual International Symposium for INCOSE, 2004*.

Doerry, N.H., 2009, Using the Design Structure Matrix to Plan Complex Design Projects, presented at ASNE Intelligent Ships Symposium 2009, Philadelphia, PA, May 20-21, 2009

McKenney, T.A., Kemink, L.F., and Singer, D.J., 2011, Adapting to Changes in Design Requirements Using Set-Based Design., *ASNE Naval Engineers Journal*, 123 (3), pp. 66-77.

Mebane, W.L., Carlson, C.M., Dowd, C., Singer, D.J., and Buckley, M.E., 2011, Set-Based Design and the Ship to Shore Connector, *ASNE Naval Engineers Journal*, 123 (3), pp. 79-92.

Singer, D.J., Doerry N. H., and Buckley, M.E., 2009. What is Set-Based Design?, *ASNE Naval Engineers Journal*, 121 (4), pp. 31-43.