Using Set-Based Design in Concept Exploration

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While Set-Based Design (SBD) has typically been applied to product development, this paper provides lessons learned in employing SBD in concept exploration, before formal product development. This paper introduces the concept of a diversity metric for measuring the collective technical risk of the feasible set of points comprising a region of a design space. This diversity metric can be used to develop a representative cost for configurations within the region of the design space. Finally the 2013 U.S. Marine Corps Amphibious Combat Vehicle (ACV) study is presented as an example of how SBD and a diversity metric were effectively employed in concept exploration.

KEY WORDS: Set-Based Design; Concept Exploration

INTRODUCTION

Set-Based Design (SBD) is increasingly being used in product development. The U.S. Navy for example, employed SBD during the preliminary design of the Ship-to-Shore Connector. (Mebane 2011) Considerable research has been conducted in SBD for product development as well. (Gray 2011)(Hannapel, Vlahopoulos, and Singer 2012) (McKenney, Kemink; and Singer 2011) However, SBD has not traditionally been employed prior to product development during the requirements development process. This paper presents an approach to using SBD principles during concept exploration where the product is a set of requirements for developing an end item, and not specifically the end-item itself. The U.S. Marine Corps Amphibious Combat Vehicle (ACV) study of 2013 is presented as an example of the method.

SET-BASED DESIGN

Designing a system can be viewed as establishing the values for a vector of design variables that define the design solution. In SBD the design solution emerges from systematically eliminating combinations of design variable values shown through analysis to NOT be a good solution. As rigorous analysis eliminates more and more of the solution space, feasible solutions become apparent. The first step in SBD is defining bounds for regions of the solution space. This can be either a bounding variable range, such as length or speed, or discrete states of design such as electric drive or traditional reduction gear driven vessel. Once the regions are established, different specialties explore tradeoffs by designing/evaluating multiple alternatives within their domain. As the specialists explore the design alternatives they communicate their analysis based preferences for different regions of the design space to the study integrators. The study integrators integrate the domain solutions produced and evaluated by specialists into total system solutions. Study integrators "integrate by intersection" by identifying intersections of the preferred variable ranges among the specialist groups. Those subsets of the variable ranges that do not fall within the intersections of preferred variable ranges are considered for "reduction" based on an assessment on the possibility that future analysis may prove solutions within the subset to be viable. (Singer et al. 2009)

Three principle concepts for implementing SBD are: (Bernstein 1998)

(1) consider a large number of potential solutions
(2) have specialists evaluate sets of solutions from their own perspective, and
(3) intersect the sets to optimize a global solution and establish feasibility before commitment. The optimization process can consider physical performance of a solution, as well as other attributes such as producibility and acquisition complexity.

Early in the design process, SBD will not result in a specific configuration; rather the solution space will still be a set of potential solutions, each called a configuration. The set should be rich enough in diversity of configurations such that additional, more detailed analysis will validate that a subset of the potential configurations still remain viable. For the purposes of this paper, a feasible configuration refers to an evaluation of a configuration based on the current fidelity of modeling and analysis. Viability refers to the evaluation of a configuration based on future more detailed modeling, analysis and testing. SBD assumes that if a configuration is declared not feasible, then it will also likely not be viable. If a configuration is declared feasible, future analysis or testing may validate the configuration as viable, or may show the configuration not to be viable.

In later stages of design where feasibility also implies viability, configurations may be eliminated based on Pareto Optimality; if a configuration is inferior in every way to another configuration, even under uncertainty, then it may be eliminated.

CONCEPT EXPLORATION

The goal of concept exploration is to establish a set of requirements, that can be realized in at least one viable configuration within schedule and budget constraints and that provide the best value. Hence the specific design parameters for a viable configuration are not important; confidence that a viable configuration exists within schedule and budget constraints is all that is needed. Later stages of design will identify the viable configurations within the set of feasible configurations.

A “capability concept,” shortened to “concept” corresponds to a complete set of requirements. A feasible concept implies that one or more feasible configurations exist that satisfy the set of requirements. Similarly, a viable concept implies that one or more viable configurations exist that satisfy the set of requirements.

Since viability depends on the results of future modeling, analysis and testing, the viability of a concept cannot be absolutely known during concept exploration. Hence an assessment that a concept is not viable is an assessment of the risk that all feasible configurations are not viable. This could happen for example, if all the feasible configurations have a common failure mechanism.

During concept exploration, multiple concepts are developed and compared. Typically, a representative cost for each concept is produced to enable performance vs cost comparisons. Value assessments based on the utility of a system meeting the set of requirements are also typically made. Finally, affordability assessments may be used to identify other funding priorities that will likely go unfunded to finance development and procurement of a configuration.

DEFINING CAPABILITY CONCEPTS

The requirements for a capability concept must be fully defined for an effective concept exploration. These requirements should be analyzed to determine which are “tradable” and which are not. Requirements that are not tradable are those where the system solution would not have significant value if the system did not meet the requirement. Concept Exploration concentrates on the tradable requirements; it assesses the combinations of tradable requirement values for feasibility, effectiveness/utility, and affordability.

A Ground Rules & Assumptions (GR&A) list documents the requirements that are not tradable in addition to other assumptions required to conduct analysis. The GR&A is typically part of the study guide defining the work for the study. See Doerry (2010) for more information on study guides.

The tradable requirements are typically sorted into two categories: High Impact and Low Impact. As implied, the range of requirement values for a high impact requirement has significant feasibility, cost, and/or effectiveness/utility impact on the system solution. Often, significant interdependency of high impact requirements exists. Low impact requirements are usually incremental; their impact on system feasibility, cost, and/or effectiveness/utility is to a large degree independent of the other requirements.

A concept exploration will thus often consist of a design space exploration for the high impact requirements and a trade-study for low impact requirements. Design of Experiments (DOE) methods can be employed to reduce the number of Capability Concepts studied. Alternately, if the degree of interdependency of the high impact requirements is not fully known, then a full search of the design space may be warranted.

Ideally, only a handful of high impact tradable requirements will exist. Initially, two or three levels should be established for each high impact tradable requirement. The differences between levels should result in significant changes in feasibility, cost and/or effectiveness/utility. To establish the final system requirements, intermediate levels of the high impact tradable requirements can always be introduced in later SBD iterations once the design space has been reduced.

The incremental impact of the low impact tradable requirements can be determined either completely independent of a specific configuration, or can be applied to one or more representative configurations. Only one representative configuration is needed if the low impact trade is truly incremental. Applying the tradable requirement to multiple configurations can be an effective test to validate that the tradable requirement is indeed incremental.

MODELING CONFIGURATIONS

A product breakdown structure (PBS) is recommended for defining the design variables for a system. The requirements can either link directly to specific design variables (i.e. the requirement is fulfilled by specifying/choosing specific values for one or more design variables), or linked to analysis performed after all the specific values for the design variables have been chosen.

Each element of the PBS should be populated with different potential solutions (components or values) for fulfilling the role of the PBS element. In some cases, the PBS element will be composed of a set of discrete solutions (i.e. a list of different engines). In other cases, the PBS element can be scalable (i.e. the capacity of a fuel tank).

A configuration for a capability concept is modeled in a two-step process. First, the component options for each element of the PBS are restricted to those that can directly fulfill the requirements of the capability concept. Second, for each element of the PBS, a component/value is chosen from the restricted set. The method of choosing the element component/value can be completely random (Monte Carlo), or can be based on an optimization algorithm. Additionally, rule sets can be employed to link the selection of different PBS elements to ensure compatibility (i.e. If you select engine A, you must select transmission X; if you select engine B, you may select either transmission Y or Z).

ANALYZING CONFIGURATIONS

Once the design variables for a configuration have been selected, the configuration is evaluated to determine feasibility, whether all of the capability concept requirements have been achieved, and to produce configuration metrics. For example a system weight for a displacement water craft can be compared to its buoyancy to determine whether it will float. Configurations that are calculated to be heavier than their buoyancy are not feasible and eliminated from further consideration. The amount of reserve buoyancy is a metric for the configuration's risk. The same water craft capability concept may have a radar cross section requirement that cannot be evaluated until the configuration is established. Hence configurations that do not meet the radar cross section requirement are eliminated from the capability concept.

Where possible, analysis should include uncertainty analysis. This uncertainty analysis can be employed to gain a better understanding of the risk of feasibility of a configuration as well as the overall risk of feasibility for the capability concept. In concept exploration, understanding the uncertainty of cost estimates is extremely important because cost is usually compared to effectiveness/utility in establishing requirements.

MODELING ENVIRONMENT

A modeling environment capable of managing the capability concepts and configurations is an important enabler of using SBD in concept exploration. One such modeling environment that has been successfully employed is the Framework for Assessing Cost and Technology (FACT) developed collaboratively by the Marine Corps Systems Command and Georgia Tech Research Institute. FACT is a framework that provides a rigorous structure to collaboratively conduct analysis of complex systems. FACT leverages the Systems Modeling Language (SysML), a widely accepted Model-Based Systems Engineering (MBSE) standard, a browser front-end and open source software to provide engineering teams a collaborative systems engineering framework. FACT enables understanding the impact of design choices on the system's cost and performance. FACT's ability to do this is predicated on the existence, availability and the ability to incorporate appropriate models and tools.

FACT is not a model. FACT integrates synthesis and analysis tools. Figure 1 highlights and expands on the three principal MBSE phases for architecting complex systems: Requirements Definition, Model Generation, and Exploration of Alternatives. To use FACT, a Work Breakdown Structure (WBS) that includes the PBS must be developed to provide a structure for the system data. Within FACT, the WBS is expressed using SysML Block Definition Diagrams (BDD). Sub-systems are defined as blocks (part properties in SysML) allowing the analysts to capture the parent-child hierarchical decomposition. Blocks are parameterized with value properties to capture the attributes required by the predictive models.

FACT exposes interdependencies among models, synthesis tools, and analysis tools through mapping inputs and outputs to attributes defined in the WBS. Users express the mapping through SysML Parametric Diagrams (PARs) and FACT executes the interdependent analyses to ensure that the results are coherent and the impacts of each parameter are propagated through all the pertinent models.

FACT provides users with the ability to define requirements and assign not only threshold and objective values, but also specify linear utilities. At present, all requirements must be associated with quantitative metrics produced by the integrated analysis tool. In some cases, these outputs are metrics for configuration feasibility, in other cases they represent total vehicle performance or effectiveness.

The WBS defines meta-data for each subsystem in the vehicle. Parts must be selected in accordance with the subsystem definitions. Users define the values for each of the design-level attributes which serve as inputs to the predictive models.

With a populated parts list, individual system configurations are created by associating one of the available parts (options) with each subsystem defined in the WBS. Multiple configurations may reference the same part. FACT explores the design space by creating multiple configurations; each configuration created by randomly or systematically selecting options for each WBS element. FACT provides data visualization of the multiple configurations, including filtering of configurations that are not feasible or violate the Ground Rules and Assumptions. A typical visualization is a scatter plot of configurations as shown in Figure 2. Other visualizations show the relative number of components within each WBS element selected for feasible configurations. These visualizations of the data are the primary product of FACT.

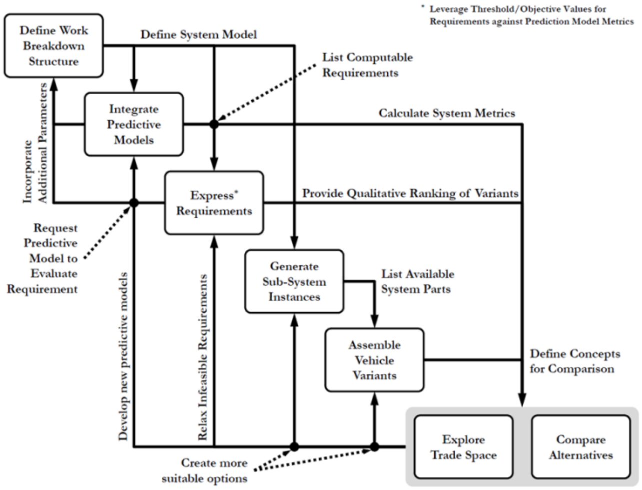


Figure 1 FACT Work Flow

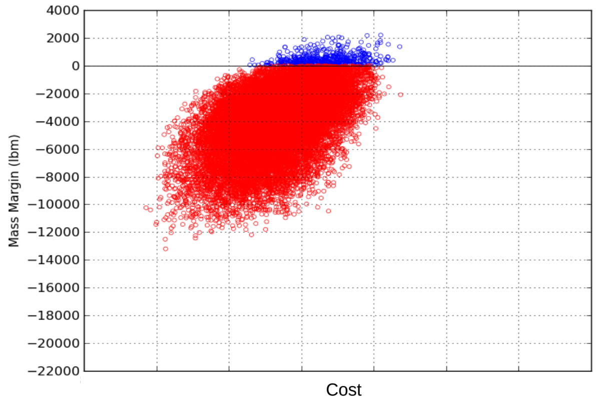


Figure 2: Scatter Diagram

MEASURING DIVERSITY ACROSS A CAPABILITY CONCEPT

A configuration is composed of m components, each of which may have one or more options. Any configuration may not be feasible; and a feasible configuration may not be viable. Multiple configurations can be graphically represented on a scatterplot as shown in Figure 3 below. Since feasibility can be assessed during the current design phase but viability cannot be ascertained until sometime later, this scatterplot will show feasible configurations that may or may not be viable. Let Ω denote the set of all of these feasible configurations and let Ω' denote a subset of configurations that meet some external criteria, e.g., cost, weight, performance. The risk of selecting an unviable configuration can be mitigated by focusing on a family of configurations with high component diversity. For example, if a vehicle is selected with an engine that becomes exceedingly expensive to manufacture, an alternate configuration with a different, affordable engine could be rapidly adopted. A diversity metric measures the relative risk of Ω' as compared to Ω by examining the number of different options used for each component in these two regions.

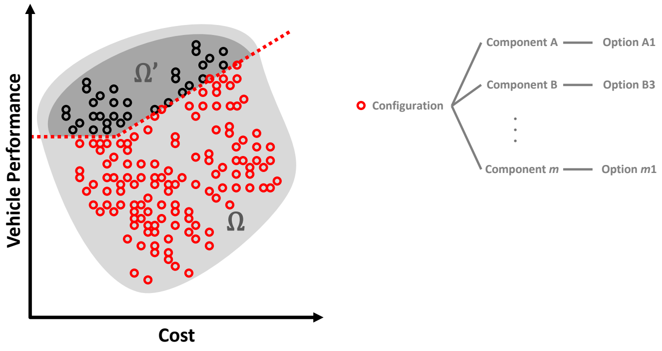


Figure 3. Example scatterplot with filtered configurations.

Component based Diversity

In creating the scatterplot of feasible configurations, possible configurations can be viewed as all the paths through the block diagram in Figure 4 where each block is labeled as i, j for component i and option j. This diagram shows m components in series where the i$^{\text{th}}$ component has n_i options and all options for a given component are in parallel. This diagram implies that some option from every component would have to be selected. To make this requirement more flexible, one option on a component could be 'None', implying that the component would not be chosen at all when that option is selected.

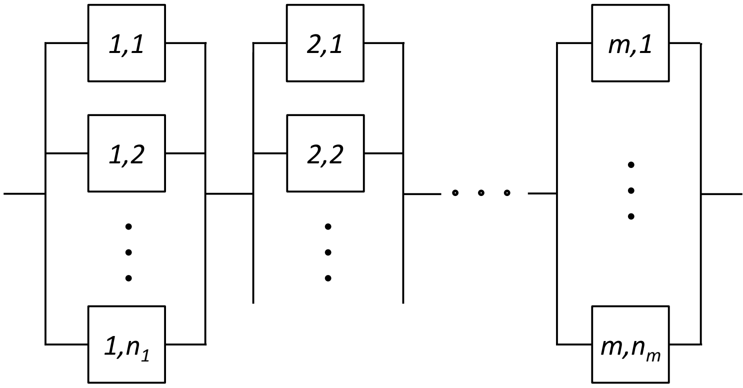


Figure 4. Block diagram representation of possible configurations.

The probability of finding a path through this system is equal to its reliability which can be expressed as

$$\prod_{i=1}^{m}\left(1-\prod_{j=1}^{n_i} pf_{ij}\right) \tag{1}$$

where pf_{ij} is the probability of option j for component i not being viable.

The region Ω considers only feasible configurations. If all the components have the same probability of not being viable, then the probability that at least one configuration is viable is

$$\prod_{i=1}^{m}\left(1-p_f^{N_i}\right) \tag{2}$$

where p_f is the probability of the selected option not being viable for a given component and N_i is the number of options for component i within Ω.

If we assume every option on every component is equally as likely to be either feasible or infeasible and set p_f to 0.5, then the probability that at least one configuration is viable is

$$\prod_{i=1}^{m}\left(1-\frac{1}{2^{N_i}}\right) \tag{3}$$

The relative diversity, D_R, of Ω' as compared to Ω is

$$D_R=\frac{\prod_{i=1}^{m}\left(1-\frac{1}{2^{n_i}}\right)}{\prod_{i=1}^{m}\left(1-\frac{1}{2^{N_i}}\right)} \tag{4}$$

where n_i is the number of options for component i within the restricted design space Ω'.

It's important to note that for any other value $p_f \in [0,1]$, the relative ranking of regions will not change.

This metric is bounded by the interval [0,1], assuming that the denominator is nonzero and therefore at least one configuration in Ω is also viable. A value of 1 represents the best possible diversity achievable with the set of components available.

Plotting results

The relative diversity for a given configuration can be defined for the region to the left and above the configuration as compared to the whole population. Left and above is ideal for this example because the preferred configuration has the highest vehicle performance for the minimum cost. Figure 5 depicts this region for the configuration represented by the black circle. This configuration has to have a diversity that is at least as high as the highest diversity of any configuration within the region bounded by the two gray lines. Therefore the coloring based on diversity must be monotonically increasing as the region grows and encompasses previously analyzed regions. Such a chart can provides decision makers insight as to how much risk they are assuming as they set requirements or establish cost estimates.

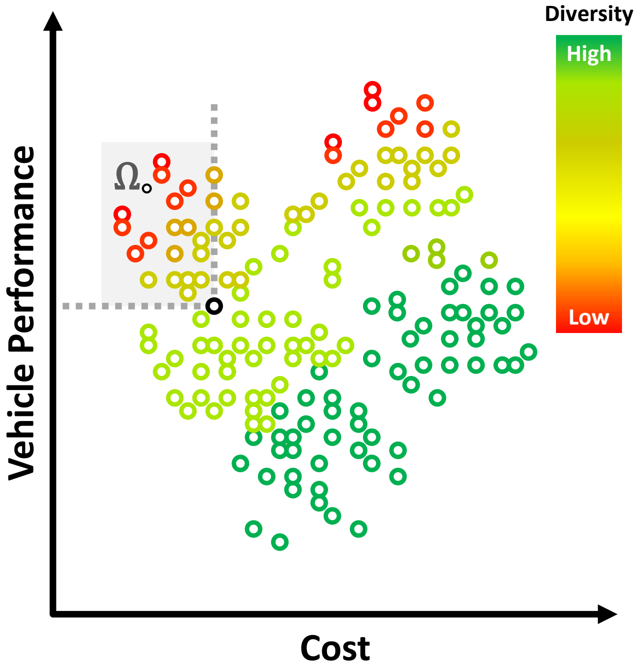


Figure 5. Example of diversity metric coloring for feasible configurations.

Other considerations

This diversity metric is not perfect. It does not consider inter-dependencies of components. For example, the region could be composed of two sets of points, one set that depends on a particular option for one component, and the other set on a particular option for a different component. Because all the configurations will be infeasible with the failure of these two options, the actual diversity could be much lower than indicated by the diversity metric.

Another issue to consider is that the points in a region will likely be a sampling of that region and not the complete set of points within that region. The degree to which the sample is representative of the complete set of points will impact the usefulness of the diversity metric. If the sample points in Ω are created using an optimization technique, care must be taken to ensure the diversity of the sample is representative of the diversity of the total population. In building Ω, a necessary number of points can be determined by sequentially increasing the sample size until the scatterplot coloring stabilizes. However, this necessary number of points may prove to not be sufficient if the optimizer is on a local optimal set of components where it could potentially miss a whole class of solutions that could increase the diversity metric.

ASSESSING VIABILITY AND COST OF A CAPABILITY CONCEPT

A capability concept is feasible if one or more of its configurations are feasible. The analysis of a configuration however, is not perfect; the estimate of performance has a degree of uncertainty. Confidence that a given configuration is feasible is enhanced if the lower bound of the configuration's estimated performance is still better than the requirement. Confidence that a capability concept is feasible is enhanced if many feasible configurations exist. If these feasible configurations have a high relative diversity or weighted relative diversity with respect to a metric (or surrogate metric) for risk, and a common mode failure is not suspected, then capability concept viability can also be presumed with high confidence.

The relative diversity metric also provides a means for developing a representative cost of a capability concept that is presumed viable. Since the relative diversity metric is a measure of technical risk, basing the representative cost on the configuration with a relative diversity metric above a threshold value ensures technical risk is captured in the cost estimate. One method used is setting the representative cost of a capability cost equal to the median value of the estimated cost of the configurations with a relative diversity metric above the threshold value. The error estimates for this cost estimate should account for both the cost estimating modeling errors and the dispersion of the (high relative diversity) configuration estimates around the median value.

FACILITATING DECISIONS

Decisions typically made during Concept Exploration are whether to proceed into product development, and if so, what the requirements should be as well as the associated target production cost and development cost. Since a capability concept represents the solution space for a requirements set, it is important to convey the technical risk of the feasibility and viability of being able to develop a product meeting the requirement set as well as the associated cost and cost risk. Scatter diagrams and diversity metrics for capability concepts can be effective in simultaneously conveying the technical and cost risk of a capability concept. It is important to ensure that the principle technical risks are effectively presented to ensure good decisions are made.

For many systems, only a few key capabilities dominate cost and technical feasibility. These capabilities should be defined and two or more levels of performance established. Capability concepts can be developed for all possible combinations of these levels of performance (full-factorial design), or design of experiments methods can be used to capture the principle impact of the key capabilities (fractional-factorial design). Defining capability concepts in this manner, if done properly, can identify cross dependencies among the key capabilities.
Other capabilities that have a lesser impact on cost and technical feasibility can often be evaluated independent of other capabilities.

EXAMPLE: ACV

Following cancellation of the Expeditionary Fighting Vehicle (EFV) program (Figure 6) in 2011, the U.S. Marine Corps explored capability trades in pursuit of a more affordable Amphibious Combat Vehicle (ACV). During 2012 the Marine Corps conducted an ACV Analysis of Alternatives (AoA) that reinforced the need for a self-deploying, survivable ACV. However, the AoA did not specifically address the value of high water speed.

Figure 6: EFV Prototype in April 2000 (Photo By: Lance Cpl. Brandon R. Holgersen).

Consequently, an ACV Directorate was created to determine the feasibility, costs, and risks of developing a survivable, high water speed (HWS) ACV. This 2013 effort included a HWS trade study which explored a design space defined by four key capabilities: the number of troops carried (2 levels), weapon system (3 variants) under-blast protection level (2 levels), and direct fire protection (2 levels). These four key capabilities were the primary technical, cost and operational effectiveness drivers. A total of twenty-four capability concepts were developed to characterize this design space using a full-factorial design (2 x 3 x 2 x 2 = 24). A Monte Carlo simulation consisting of 20,000 randomly generated configurations from a database of components was developed for each capability concept. For those capability concepts that were projected to have configurations with a positive mass margin (planing weight minus vehicle weight), an optimization algorithm was used to more fully populate the design space with positive mass margin configurations. Each capability concept was assigned a feasibility category of "Feasible," "High Risk Feasibility," or "Not Feasible" depending on the peak mass margin generated. The results for all twenty-four capability concepts are shown in Table 1. Scatter diagrams for feasible, high risk feasibility, and not feasible capability concepts are shown in Figure 7, Figure 8, and Figure 9.

Table 1: Feasibility Assessment of HWS Trade Study Capability Concepts

Capabilities	14 Troops; "A" Direct Fire Protection	14 Troops; "B" Direct Fire Protection	17 Troops; "A" Direct Fire Protection	17 Troops; "B" Direct Fire Protection
"C" Under-Blast Protection; Weapon "X"	**Feasible**	**Feasible**	**Feasible**	**High Risk Feasibility**
"C" Under-Blast Protection; Weapon "Y"	**Feasible**	**Feasible**	**Feasible**	**High Risk Feasibility**
"C" Under-Blast Protection; Weapon "Z"	**High Risk Feasibility**	**Not Feasible**	**Not Feasible**	**Not Feasible**
"D" Under-Blast Protection; Weapon "X"	**High Risk Feasibility**	**Not Feasible**	**Not Feasible**	**Not Feasible**
"D" Under-Blast Protection; Weapon "Y"	**High Risk Feasibility**	**Not Feasible**	**Not Feasible**	**Not Feasible**
"D" Under-Blast Protection; Weapon "Z"	**Not Feasible**	**Not Feasible**	**Not Feasible**	**Not Feasible**

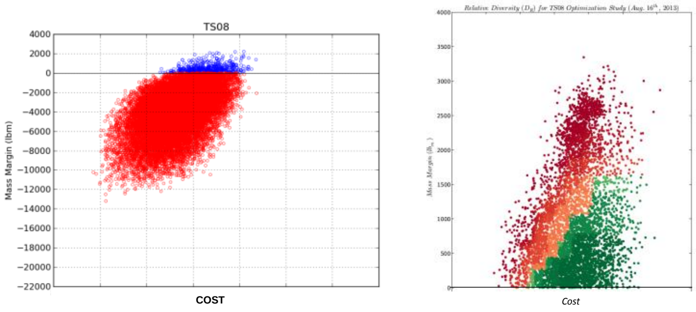


Figure 7: Scatter Diagrams for a "Feasible" Capability Concept

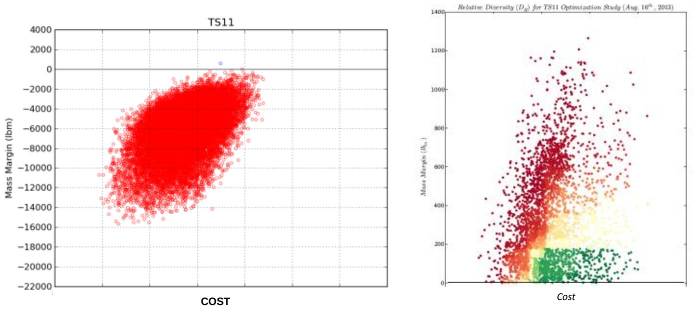


Figure 8: Scatter Diagrams for a "High Risk Feasibility" Capability Concept

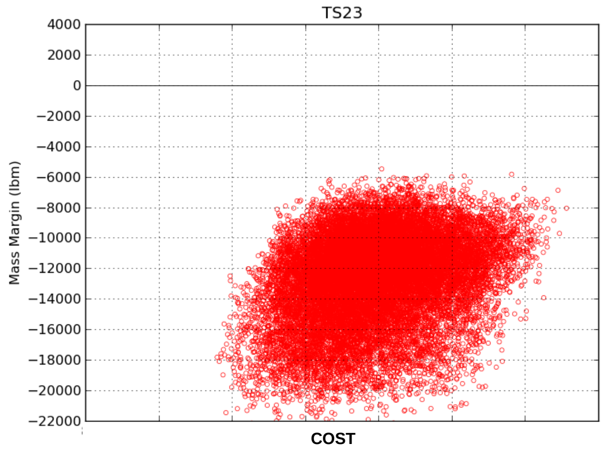
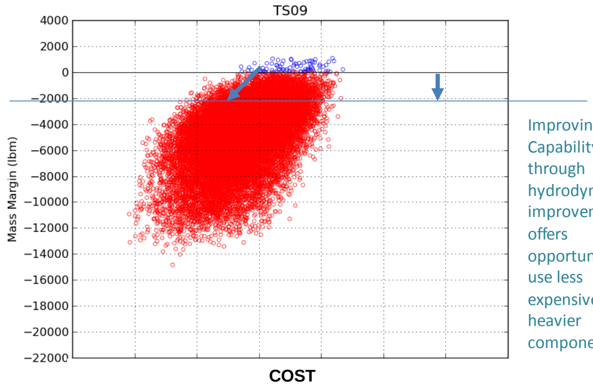


Figure 9: Scatter Diagram for a "Not Feasible" Capability Concept

One of the important insights from the scatter diagrams is shown in Figure 10. Should changes to the hydrodynamic (and hydrostatic) performance of the ACV increase the planing weight, then this additional weight capacity can be used to incorporate heavier, but less expensive components, or used to improve the capability of the ACV. For the scatter plots, increasing the planing weight shifts the Y-axis downwards and changes the top "red" points into "blue" points.



Improving Lift Capability through hydrodynamic improvements offers opportunity to use less expensive but heavier components.

Figure 10: Impact of Hydrodynamic Improvements on Scatter Diagram

Separately, 28 other capabilities of lesser impact were identified for future analysis. For each of these capabilities, representative cost and weight impacts were estimated independent of the four key capabilities.

FUTURE WORK

The methods described in this paper proved very useful in the concept exploration of the ACV. To fully generalize these methods however, the following work is recommended:

1. To improve the probability that feasibility implies viability, incorporate more detailed synthesis and analysis processes into the development of a configuration without significantly increasing the computational time.

2. Better identify common mode failure opportunities for a set of configurations. Develop methods for identifying the risk of failure of a given component.

3. Develop better methods of developing representative costs for different configurations that represent the same level of risk; particularly when considering multiple risks.

4. Developing methods to ensure that optimizers generate sets of feasible configurations that are representative of the feasible design space.

CONCLUSIONS

Although SBD has typically been applied to product development, it is also applicable to earlier concept exploration where the end products are a set of requirements, risk assessments, and associated cost estimates. SBD during concept exploration enables an assessment of capability concept viability even when the viability of any particular feasible configuration cannot be established. A diversity metric is presented as a surrogate for technical risk which can be used to establish cost estimates that can be compared among capability concepts. The ACV 2013 studies illustrate how SBD was actually applied during concept exploration of a complex system.

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REFERENCES

Bernstein, Joshua I., " Design Methods in the Aerospace Industry: Looking for Evidence of Set-Based Practices ," Thesis, MIT, May 1998.

Doerry, Dr. Norbert, "Guide for Conducting Technical Studies," Naval Sea Systems Command, SEA 05 Technology Group, Ser 05T / 33 of 27 December 2010.

Gray, Alexander Westley, " Enhancement of Set-Based Design Practices Via Introduction of Uncertainty Through the Use of Interval Type-2 Modeling and General Type-2 Fuzzy Logic Agent Based Methods." PhD dissertation, Naval Architecture and Marine Engineering, University of Michigan 2011.

Hannapel, Shari E., Nickolas Vlahopoulos, and David J. Singer, " Including Principles of Set-Based Design in Multidisciplinary Design Optimization," AIAA 2012-5444, 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSM 17 - 19 September 2012, Indianapolis, Indiana.

McKenney, Thomas A.; Lauren F. Kemink; and David J. Singer, “Adapting to Changes in Design Requirements Using Set-Based Design,” Naval Engineers Journal, Volume 123, Number 3, September 2011 , pp. 67-77.

Mebane, Walter L., Craig M. Carlson; Chris Dowd, David J. Singer, and Michael E. Buckley, “Set-Based Design and the Ship to Shore Connector,” Naval Engineers Journal, Volume 123, Number 3, September 2011 , pp. 79-92.

Singer, David J. PhD., Captain Norbert Doerry, PhD., and Michael E. Buckley," What is Set-Based Design?," Presented at ASNE DAY 2009, National Harbor, MD., April 8-9, 2009. Also published in ASNE Naval Engineers Journal, 2009 Vol 121 No 4, pp. 31-43.