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Measuring Diversity in Set-Based Design

ABSTRACT

Within the past few years Set-Based Design (SBD) has been employed in several Concept Exploration studies to gain an understanding of the cost, affordability, military effectiveness, and technical feasibility of different sets of requirements. In applying SBD to Concept Exploration, a capability concept describes a set of requirements, associated CONOPS, employment strategy, acquisition strategy, and support strategy. Concept Exploration assesses the feasibility of producing a physical system meeting the capabilities described in the capability concept, develops representative costs for a feasible physical system, and assesses the operational utility of a system achieving the capabilities of the capability cost. Feasibility is an assessment that a configuration will be successful given the level of analysis performed. A feasible configuration may later prove not to be a viable configuration when additional analysis and/or testing are performed.

One goal of Concept Exploration is to compare a number of different capability concepts. To compare costs, a representative cost, or cost range, must be developed for each capability concept. Since many feasible configurations usually exist for a feasible capability concept, a method is needed to develop a representative cost for the set of feasible configurations. This paper defines a diversity metric and provides an algorithm using the diversity metric for developing a representative cost for a capability concept. Two examples are provided to demonstrate the algorithm.

INTRODUCTION

Set-Based Design (SBD) is increasingly being employed in early stage and preliminary design of naval ships, craft, and amphibious vehicles. Mebane et al. describes the application of SBD to the preliminary design of the Ship-to-Shore Connector (SSC). Burrow et al. and Doerry et al. detail how SBD was employed in the concept exploration of the Amphibious Combat Vehicle. More recently, SBD was also employed by the Small Surface Combatant Task Force (SSCTF) to explore alternative small surface combatants.

In SBD, the design solution is arrived at from systematically eliminating combinations of design variable values (a configuration) shown through analysis to NOT be a good solution. A configuration is not a good solution if it is not feasible, or if it is heavily Pareto dominated by other solutions such that many feasible configurations are superior (including in cost). As rigorous analysis eliminates more and more of the solution space, feasible, and eventually viable configurations become apparent. Unlike many traditional design methods which focus on choosing configurations based on a calculated Pareto front as depicted in Figure 1, SBD recognizes that the understanding of the design space in early stage design is inadequate to precisely locate the Pareto front. Instead SBD seeks to gain sufficient information to eliminate the highly infeasible and the highly dominated solutions. With each iteration, additional analysis and/or testing enables elimination of more infeasible and dominated solutions. The Pareto front emerges as part of the design method. (McKenney and Singer 2014)

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

(1) consider a large number of configurations
(2) have specialists evaluate sets of configurations from their own perspective, and

(3) intersect the sets to optimize a global solution and establish feasibility before commitment.

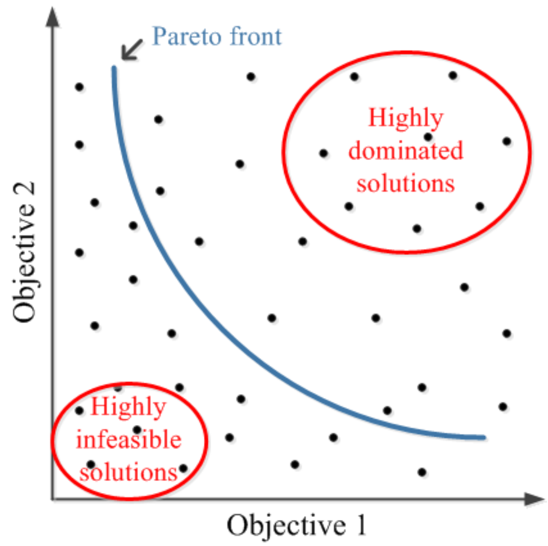

Figure 1: SBD Concept (McKenney and Singer 2014)

During concept exploration, sets of performance requirements and associated Concepts of Operation (CONOPS), called "capability concepts" are compared. Early in the design process, SBD will not result in a specific configuration for a capability concept; rather the solution space for a capability concept will still be a set of feasible configurations. Hence when employing SBD during concept exploration, capability concepts are compared by examining the properties of sets of configurations, not of specific configurations.

Additionally, SBD recognizes the difference between a configuration being feasible and being viable. As described by Doerry et al. (2014), 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. A capability concept is feasible if the set of configurations is rich enough in diversity such that the probability that all feasible configurations are not viable is very low.

Identifying a capability concept which can be realized in at least one viable configuration within schedule and budget constraints and that provides the best value is usually one goal of concept exploration. The specific design parameters for a viable configuration are not the end product; rather confidence that a viable configuration exists within schedule and budget constraints is all that is usually needed. Continuing SBD in later stages of design will result in finding the viable configurations from within the set of feasible configurations.

Since future modeling, analysis and testing is required to establish viability, the viability of a configuration, and by extension a capability concept, cannot be absolutely known during concept exploration. Hence an assessment that a capability concept is not feasible is an assessment of the risk that all feasible configurations are not viable or that there are no feasible configurations. A common failure could result in all feasible configurations not being viable.

During concept exploration, multiple capability concepts are developed and compared. Typically, a representative cost for each concept is produced based on the set of feasible configurations 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. The combination of cost, value, and affordability are used to choose one or a few capability concepts for further refinement during the next stage of design.

This paper focuses on developing a representative cost for a capability concept based on a diversity metric applied to the set of feasible configurations for the capability concept. The diversity metric measures the degree to which alternate choices for components exist within a set of feasible configurations. A higher value for the diversity metric implies that if future analysis or testing of a component shows the component will not work, or if the component can no longer be procured at the estimated cost, then substitutions for the component are more likely available and can be accommodated within the representative cost. The representative cost is established at a level such that the probability is very small that all feasible configurations with an estimated cost below the representative cost are not viable. In this manner the representative cost reflects only feasible configurations that are not heavily dominated by other configurations; the configurations that have a very high cost, but do not significantly reduce risk are excluded in calculating the representative cost. A simple example of the process for which the calculations can be easily understood is presented as Appendix A. A more complex example is included in the text.

MODELING CONFIGURATIONS

In developing a diversity metric, a product breakdown structure (PBS) is used to define 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. An example of the former is including a specific weapon system which meets the requirement to counter a specific threat. An example of the latter is the requirement for a ship to be stable which is a function of hullform, weight, and center of gravity; the weight and center of gravity will not be known until a weight and stability analysis is done after all the design variables are established.

Different potential solutions (components or values) should exist for each element of the PBS. 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, where possible, the component options for the PBS elements are restricted to those that can directly fulfill 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 produce configuration metrics (such as cost) and to determine feasibility. 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. 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 from the capability concept are not feasible.

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.

ANALYZING CAPABILITY CONCEPTS

A configuration is represented by a set of design variables, each of which may have been selected from one or more options. A 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 2 where the blue points represent feasible configurations and the red points configurations that are not feasible[1]. All of the blue points are assessed to meet the requirements of the capability concept. Since feasibility can be assessed during the current design phase but viability cannot be determined until sometime later, many configurations that are not viable are represented by blue points; the viable configurations are hidden among the set of blue points.

If all the feasible configurations (blue points) were viable and the cost estimates accurate, the optimal configuration would be represented by the blue point with the lowest cost; it would Pareto dominate all other configurations since all of the blue points meet the same capability concept requirements and this configuration is the least expensive. The cost of this optimal configuration would be an appropriate representative cost of the capability concept; a better solution may exist that is not included in the set of generated feasible (and viable) configurations, but it would have to cost less than the representative cost (Many sampling methods, such as the Monte Carlo method, are not efficient in finding extreme cases; lowest cost in this case).

Unfortunately, the viability of a feasible configuration is not known, hence choosing the lowest cost feasible configuration as a representative cost assumes considerable cost risk. Choosing a higher representative cost reduces this risk because more feasible configurations have the same or less cost; the chances that all the configurations are not viable decreases as a higher representative cost is chosen (and more potentially viable configurations are included in the set of points with a cost less than the representative cost).

The fundamental issue is identifying how much higher in cost one should set the representative cost above the least costly feasible configuration. A too low of a value implies a greater risk that all the configurations below the representative cost may prove not viable. A too high of a value implies that highly dominated configurations that do not significantly reduce risk are incorporated and assigning a higher than necessary cost to the capability represented by the capability concept. A too high of a value may result in poor decisions with respect to deciding which capability concepts to pursue.

The representative cost should be set high enough, but no higher, such that the risk of all the lower cost configurations being not viable is low. This goal can be achieved by focusing on a family of configurations with high component diversity. For example, if a vehicle is selected with an engine that

[1] While this example is limited to two dimensions for illustrative purposes, the concept is directly scalable to an arbitrary number of dimensions.

becomes exceedingly expensive to manufacture, an alternate configuration with a different, relatively inexpensive engine could be rapidly adopted. A diversity metric measures the relative risk of all the feasible configurations within a region later proving to be not viable by evaluating how different the configurations are from each other. A greater number of possible ways of configurations meeting the capability concept requirements reduces the risk of all configurations proving to be not viable.

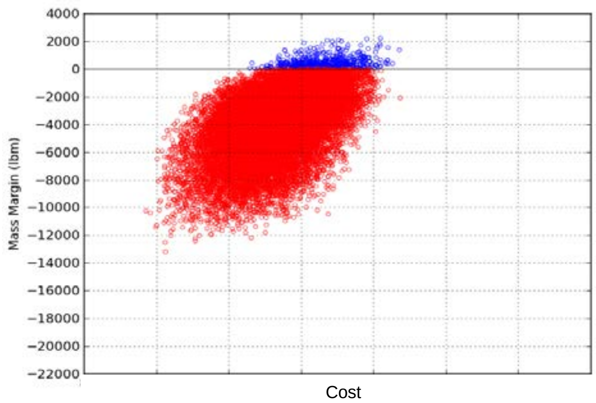

Figure 2: Scatter Plot

In devising a diversity metric, the introduction of a new component alternative that does not result in less expensive configurations and does not reduce risk should not result in a significant change to the representative cost. The representative cost should be insensitive to the creation of new highly dominated configurations. For this reason, using the mean or median value of all feasible configurations is not an ideal method for creating a representative cost. Instead the method should either directly or indirectly account for risk.

MEASURING DIVERSITY

This paper proposes a diversity metric based on selecting a subset of configurations that include multiple options for all or some of the design variables varied in the configuration synthesis (such as through Monte Carlo Simulation). For the purposes of this paper these variables will be called "Diversity Variables." The current formulation of the diversity metric requires the diversity variables to be discrete. Variables that are normally continuous can be converted into discrete variables by limiting the configuration synthesis process to a discrete number of values. Ideally, the continuous design variable values should be aligned with a degree of risk that is common across configurations. For example a weight margin should usually be expressed as a percentage rather than an absolute value; a specific value for one design may be significantly less or more risky than the same value for another design. One could then elect to choose multiple values for weight margin percentage as the discrete values for the diversity variable.

Some design variables that are varied in the configuration synthesis process need not be included in the list of Diversity Variables. These variables are typically not "alternatives" but are variables where suitability is not known until feasibility assessments are made after a configuration is synthesized. The dimensions of a ship, for example, are not in themselves usually good diversity variables. For many synthesis algorithms, the ship dimensions are used as inputs, then feasibility assessments are used to screen out the configurations that "do not work." In this case, the design margins employed in the feasibility assessment would be better diversity variables.

Examples of good diversity variables include:
- The list of potential engines that could be used
- A list of combat systems elements that could be used and still possibly meet capability concept requirements
- A discrete list of design margin values
- A list of material choices for the structure
- A list of architectures for subsystems
- A list of options for a design parameter that has large impact on the design, has not been specified by the capability concept but must be decided at some later date. (e.g. the ability of a ship to survive whipping - if not specified)

Once the list of diversity variables has been developed, each diversity variable is examined and assigned two parameters to filter the set of feasible configurations into a subset:

> MIN_NBR_OPTIONS = the minimum number of options for the diversity variable that must be represented in the subset.
> MIN_NBR_CONFIGS_PER_OPTION = For each of MIN_NBR_OPTIONS options for the diversity variable, the subset must have a minimum of MIN_NBR_CONFIGS_PER_OPTION configurations.

The value for MIN_NBR_OPTIONS should be based on the likelihood that each individual option may prove not to work within the design. If the risk is low, then a value of 2 is probably sufficient. If the risk is moderate then a value of 3 is probably sufficient. If the risk is high then a higher value may be warranted. Obviously, MIN_NBR_OPTIONS cannot exceed the number of options available for the diversity variable within the set of feasible configurations.

The value for MIN_NBR_CONFIGS_PER_OPTION should be set to a value to prevent consideration of options that are only marginally feasible and present in only a very few feasible configurations. A value on the order of the total number of diversity variables is probably a reasonable starting point; the impact of a larger value is discussed in the EXAMPLE section below.

Once MIN_NBR_OPTIONS and MIN_NBR_CONFIGS_PER_OPTION have been assigned to each of the n design variables, the BASE_SUM can be calculated:

$$BASE\_SUM \;=\; \sum_{i=1}^{n} MIN\_NBR\_OPTIONS_i \cdot MIN\_NBR\_CONFIGS\_PER\_OPTION_i$$

The feasible configurations are ordered from lowest cost to highest cost, then examined one by one to generate a DIVERSITY_SCORE for each configuration. For each diversity variable a list is developed that has an element for each option of the diversity variable. The element is set equal to the number of previous configuration and the current configuration that includes the diversity variable option. DV_NBR_METRIC is calculated by selecting the MIN_NBR_OPTIONS number of the highest list elements; then adding together the minimum of MIN_NBR_CONFIGS_PER_OPTION and the list element value. The DIVERSTIY_SCORE is the sum of DV_NBR_METRIC for all of the diversity variables.

The DIVERSITY_METRIC for a configuration is the DIVERSITY_SCORE divided by the BASE_SUM. For the first configuration (lowest cost) the DIVERSITY_METRIC is equal to the number of diversity variables divided by BASE_SUM. The DIVERSITY_METRIC will monotonically increase with each configuration in ascending order of cost[2]. Once all the MIN_NBR_OPTIONS and MIN_NBR_CONFIGS_PER_OPTION values are achieved, the DIVERSITY_METRIC has value 1.0. All configurations with a greater cost will still have a DIVERSITY_METRIC of 1.0.

While a DIVERSITY_METRIC is assigned to each configuration, its value is based on its own configuration and all the configurations that have a lower cost. The DIVERSITY_METRIC is therefore a measure of the design space consisting of the configuration the metric is assigned to and all configurations with a lower cost. If a new component is introduced into the design space that results in lower cost configurations, then the DIVERSITY_METRIC for a given configuration may change even though its own configuration has not. What has changed is the option to replace a component with one that will result in a less expensive configuration. In this sense, the DIVERSITY_METRIC reflects the value of a design option.

Even with a DIVERSITY_METRIC of 1.0, it is possible that all the configurations with a lower cost are not viable. This can occur if a common mode failure impacts all of the configurations, or if low cost options for multiple components prove not to work, requiring the simultaneous replacement of a multiple number of low cost component options with high cost component options.

ESTABLISHING A REPRESENTATIVE COST

The diversity metric can be employed in several ways to establish a representative cost for a capability concept. This paper will present two methods: Direct assessment and an indirect assessment. The direct assessment method is appropriate where the difference in cost associated with different component options is not excessive. If component options have cost impacts that differ substantially, the indirect assessment approach may be more appropriate.

In the direct assessment, the representative cost is established by taking the cost for a specific value of the diversity metric. Using the lowest cost associated with a diversity value of 1.0 would usually be a conservative estimate if there is a strong probability that the low cost impact components will work. Expressing the representative cost as a range with the low end associated with a diversity value of 0.75 and a high end of 1.0 would normally be reasonable, assuming the component options are chosen such that their probability of working correctly is high.

In the indirect assessment, a subset of the feasible configurations is extracted to develop an average cost and standard deviation. For each component, only the component options that first meet the MIN_NBR_OPTIONS and MIN_NBR_CONFIGS_PER_OPTION criteria are retained. All feasible configurations that do not have the retained component options are eliminated. The mean value and standard deviation of the cost of the remaining subset of feasible configurations are then used as the representative cost. Note that this method may drop from consideration some feasible configurations with a diversity metric below 1.0 and may include multiple options with a diversity metric of 1.0. In general the indirect assessment will result in a higher estimate since in calculating the average, the likelihood of having to use all the highest cost impact components is weighted equally to the being able to use all the lowest cost components. If there is a strong probability that the lowest cost components will work, then the indirect assessment will be too conservative.

Note that both the direct assessment and the indirect assessment methods are insensitive to the creation of new highly dominated configurations. If an expensive component options is introduced that rarely is

[2] While the DIVERSITY_METRIC will never decrease, it can remain constant if the configuration does not increase the DV_NBR_METRIC for at least one diversity variable.

incorporated in a configuration with a diversity metric below 1.0, then it will neither impact the cost associated with a given level of diversity, nor will it be included in the retained list of components in the indirect assessment method.

Many cost models provide a most likely value and a "tolerance" delta to account for sensitivities of the cost model to unknowable and/or uncertain parameters (cost of labor in the future, price of oil in the future, cost of steel in the future, etc.). in the direct assessment method, some or all of the tolerance delta may be applied to the lower and upper bounds. If the tolerance delta is interpreted as a standard deviation, then it can be combined with the standard deviation for the indirect method by taking the square root of the sum of the squares of the standard deviation of the cost estimate and the standard deviation of the costs of the indirect method configurations.

EXAMPLE

The diversity metric was applied to a dataset of 51,000 feasible configurations for a surface combatant generated from a set of response equations derived from the Rapid Ship Design Environment (RSDE) and the Advanced Ship and Submarine Evaluation Tool (ASSET). For details on RSDE/ASSET, see (Gray et al. 2013). All 51,000 configurations have been evaluated as feasible based on the same set of capability concept requirements. The diversity variables are listed in Table 1. The dataset is portrayed in Figure 3. Note that cost is normalized.

Table 1: Complex Example Diversity Variables

Diversity Variable	Total Number of Options	MIN_NBR_OPTIONS	MIN_NBR_CONFIGS_PER_OPTION
Propulsion Architecture	5	4	10
Weight Equation	2	2	10
Main Engine Power	6	3	10
Hogging Constant	2	2	10
Deckhouse Material	2	2	10
AAW suite	8	3	10
ASW suite	6	3	10
SUW suite	7	3	10

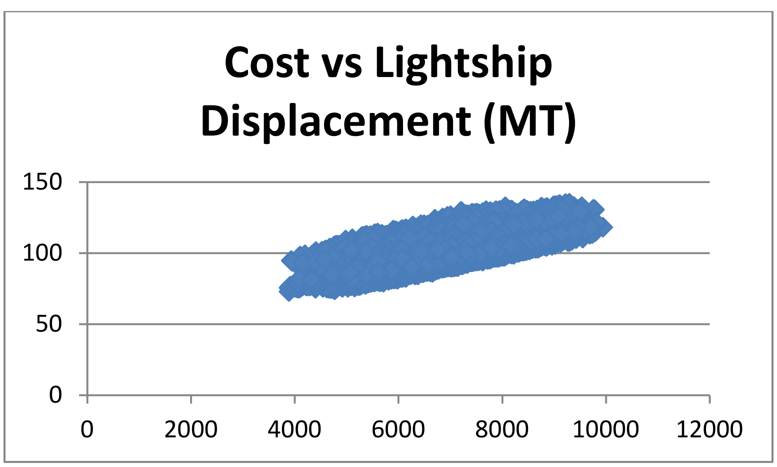

Figure 3: Complex Example Data Set

In applying the process for calculating the diversity metric, 164 configurations were necessary to achieve a diversity metric of 1.0. The order that the diversity fields met their constraint is shown in Table 2. Table 2 suggests that near term design activities should concentrate on analysis, simulation and testing to better understand the component options for the "Hogging Constant," "Main Engine Power," and "Propulsion Architecture," since these diversity variables have large impact on cost. Detailed analysis of the combat systems suites (AAW, SUW, ASW) can likely be deferred as long as the design is capable of integrating any one of the three component options identified in the diversity analysis for each suite.

Using the direct assessment, the cost range is between 76.6 and 78.6. For the indirect assessment, all but 3352 of the 51,000 configurations are eliminated. The average cost using the indirect method is 90.4 with a standard deviation of 6.7. As expected, the indirect assessment results in a more conservative representative cost since it weights the configurations with high cost component options the same as configurations with low cost component options.

Table 2: Order in meeting criteria

Diversity Variable	Number of Configurations to meet criteria
AAW suite	40
SUW suite	43
ASW suite	51
Weight Equation	54
Deckhouse Material	57
Propulsion Architecture	119
Main Engine Power	153
Hogging Constant	164

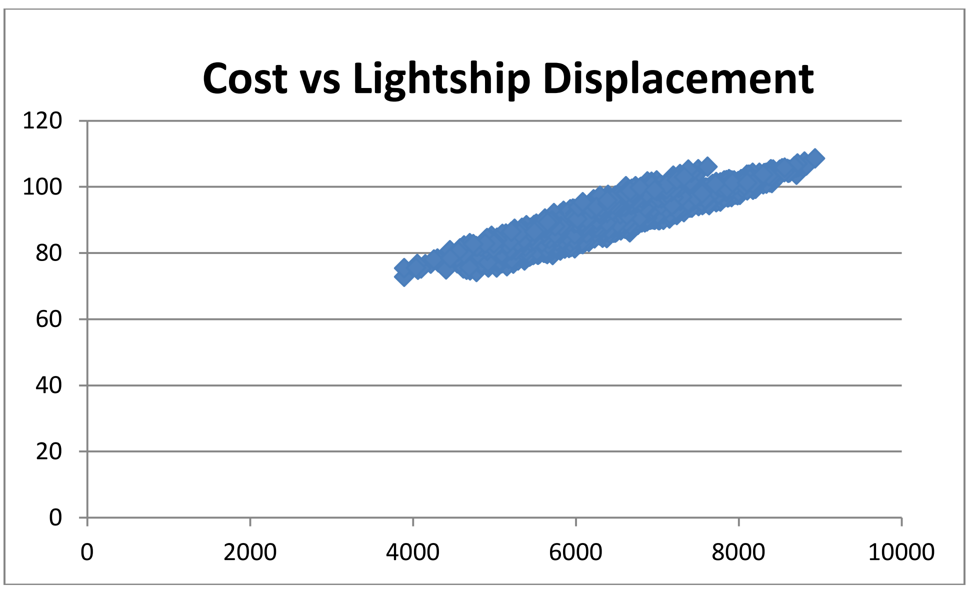

Figure 4: Complex Example Indirect Assessment Reduced Data Set

The sensitivity of the results to varying MIN_NBR_CONFIGS_PER_OPTION was examined by recalculating the diversity metric using a value of 100 instead of 10 for MIN_NBR_CONFIGS_PER_OPTION for every diversity variable. While the order of diversity variables achieving MIN_NBR_OPTIONS and MIN_NBR_CONFIGS_PER_OPTION changed somewhat (Table 3), the subset of component options that fulfilled the criteria remained the same. As a result, the representative cost using the indirect assessment did not change at all. The representative cost range using the direct assessment method is 79.6 to 81.7. As expected the direct assessment representative costs increase (76.6 to 78.6 for MIN_NBR_CONFIGS_PER_OPTION = 10) since more costly configurations must be included to achieve a given diversity metric value.

Table 3: Order in meeting criteria with MIN_NBR_CONFIGS_PER_OPTION = 100

Diversity Variable	Number of Configurations to meet criteria
Deckhouse Material	329
Weight Equation	397
AAW suite	454
SUW suite	521
ASW suite	574
Hogging Constant	756
Main Engine Power	808
Propulsion Architecture	853

The sensitivity of the results to varying MIN_NBR_OPTIONS was examined by recalculating the diversity metric using a MIN_NBR_OPTIONS value of 2 and a MIN_NBR_CONFIGS_PER_OPTION value of 100 for every diversity variable. The order of diversity variables achieving their criteria changed significantly (Table 4). The Propulsion Architecture diversity variable, which previously required four component options, became the first to meet the criteria. Note that for a given diversity variable, the number of configurations needed to meet its criteria does not depend on the MIN_NBR_OPTIONS of the other design variables.

The representative cost range using the direct assessment method is now 79.2 to 81.5 . For the indirect assessment, only 422 configurations are retained. The average cost of these 422 configurations is 88.8 with a standard deviation of 6.7. As expected, reducing MIN_NBR_OPTIONS will result in a lower representative cost for both the direct assessment and the indirect assessment.

Table 4: Order in meeting criteria with MIN_NBR_OPTIONS = 2 and MIN_NBR_CONFIGS_PER_OPTION = 100

Diversity Variable	Number of Configurations to meet criteria
Propulsion Architecture	315
Deckhouse Material	329
Weight Equation	397
SUW suite	399
ASW suite	408
AAW suite	421
Main Engine Power	550
Hogging Constant	756

SUMMARY AND FUTURE WORK

This paper has presented a method for calculating a diversity metric for a set of configurations and applying that diversity metric to develop a representative cost for the capability concept for which the set of configurations is designed to meet. The representative cost can be used to compare multiple capability concepts. Two methods for developing a representative cost are presented: a direct assessment and an indirect assessment. The direct assessment method is easier to calculate and is reasonable if the probability is high that components with a low cost impact will be successful. The representative cost range produced by the direct assessment is influenced by the selection of MIN_NBR_CONFIGS_PER_OPTION. The indirect assessment method has the advantage of being much less sensitive (if at all) to MIN_NBR_CONFIGS_PER_OPTION but may be too conservative if the probability of the component options with the least cost impact proving to be not viable is extremely low.

In addition to developing a representative cost, the process for creating the diversity metric also provides insight of which components should be analyzed, simulated, and/or tested first to best narrow the representative cost range within the context of Set-Based Design.

For future work, the indirect method can be improved by taking a weighted average instead of a simple average. The configurations employing lower cost impact diversity variable options should be weighted more than those employing higher cost impact diversity variable options. The weight should be related to an assessment of the probability that the low cost impact diversity variable will prove to be viable. This weighted average should result in a less conservative, but more realistic representative cost.

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APPENDIX A: SIMPLE EXAMPLE

Table 5 lists an example of a set of 24 feasible configurations reflecting different options for three components: Component A, Component B, and Component C. Component A has 3 options, Component B has 2 options and Component C has 4 options.

Table 5: Simple Example Table of Configurations

CONFIG_ID	COMPONENT A	COMPONENT B	COMPONENT C	COST
1	A1	B1	C1	111
2	A1	B2	C1	121
3	A2	B1	C1	211
4	A2	B2	C1	221
5	A3	B1	C1	311
6	A3	B2	C1	321
7	A1	B1	C2	112
8	A1	B2	C2	122
9	A2	B1	C2	212
10	A2	B2	C2	222
11	A3	B1	C2	312
12	A3	B2	C2	322
13	A1	B1	C3	113
14	A1	B2	C3	123
15	A2	B1	C3	213
16	A2	B2	C3	223
17	A3	B1	C3	313
18	A3	B2	C3	323
19	A1	B1	C4	114
20	A1	B2	C4	124
21	A2	B1	C4	214
22	A2	B2	C4	224
23	A3	B1	C4	314
24	A3	B2	C4	324

If MIN_NBR_OPTIONS is set to 2 and MIN_NBR_CONFIGS_PER_OPTION is set to 2 for all three components, the resulting diversity metric vs cost plot is shown in Figure 5 and the associated data in Table 6. Note that configurations 13, 19, 14 and 20 do not increase the diversity metric because component options C3 and C4 are not needed to achieve the MIN_NBR_OPTIONS criteria. Also note that component A3 which results in highly dominated configurations, is not present in any configuration with a diversity metric below 1.0.

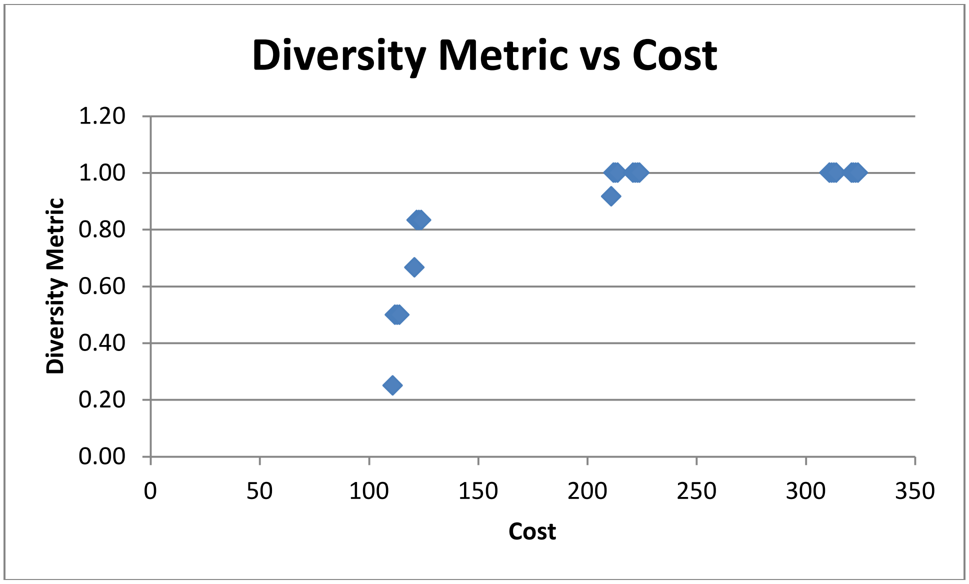

Figure 5: Simple Example Diversity Metric Vs Cost

Table 6: Simple Example Diversity Metric Table

CONFIG_ID	COMPONENT A	COMPONENT B	COMPONENT C	COST	Diversity Metric
1	A1	B1	C1	111	0.25
7	A1	B1	C2	112	0.50
13	A1	B1	C3	113	0.50
19	A1	B1	C4	114	0.50
2	A1	B2	C1	121	0.67
8	A1	B2	C2	122	0.83
14	A1	B2	C3	123	0.83
20	A1	B2	C4	124	0.83
3	A2	B1	C1	211	0.92
9	A2	B1	C2	212	1.00
15	A2	B1	C3	213	1.00
21	A2	B1	C4	214	1.00
4	A2	B2	C1	221	1.00
10	A2	B2	C2	222	1.00
16	A2	B2	C3	223	1.00
22	A2	B2	C4	224	1.00
5	A3	B1	C1	311	1.00
11	A3	B1	C2	312	1.00
17	A3	B1	C3	313	1.00
23	A3	B1	C4	314	1.00
6	A3	B2	C1	321	1.00
12	A3	B2	C2	322	1.00
18	A3	B2	C3	323	1.00
24	A3	B2	C4	324	1.00

Using the direct assessment method, the representative cost for this capability concept would range between 122 (first configuration with a diversity metric > 0.75) and 212 (first configuration with a diversity metric = 1.0)

In the indirect method, component options A3, C3, and C4 would be eliminated, resulting in the eight remaining configurations shown in Table 7. For these remaining configurations, the mean value is 166.5 and the standard deviation is 53.7. Adding and subtracting the standard deviation from the mean results in an estimated range between 113 and 220.

Table 7: Simple Example Indirect Method Configurations

CONFIG_ID	COMPONENT A	COMPONENT B	COMPONENT C	COST	Diversity Metric
1	A1	B1	C1	111	0.25
7	A1	B1	C2	112	0.50
2	A1	B2	C1	121	0.67
8	A1	B2	C2	122	0.83
3	A2	B1	C1	211	0.92
9	A2	B1	C2	212	1.00
4	A2	B2	C1	221	1.00
10	A2	B2	C2	222	1.00

The order in which the components satisfy the MIN_NBR_OPTIONS and MIN_NBR_CONFIGS_PER_OPTION criteria provides additional insight on which components to concentrate risk mitigation activity. For the simple example, configuration 8 results in both Components B and C fulfilling their criteria, while Component A's criteria are not fulfilled until configuration 9. Conducting analysis, simulations, and/or experiments to establish whether or not component option A1 will prove viable or not has great value in narrowing the range of the representative cost. The temptation to prematurely eliminate component option A2 should be resisted; it should be retained as an option until the viability of component option A1 has been established with high certainty.