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Evolution of a Survey for Self-Reported Engineering Design Space Exploration Tendency

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The objective of this research is to develop a survey consisting of statements that provide insight into an individual's design space exploration tendency. There are formal exercises to evaluate design space exploration, but these exercises are resource intensive, time consuming, challenging to deploy and difficult to process the results. The survey instrument is intended to address several of these challenges. To develop the survey instrument, the Shah-Vargas (SV) metrics of engineering ideation effectiveness were used as a basis for quantifying engineering Design Space Exploration (DSE). These metrics are 1) Quantity – the number of ideas generated, 2) Quality – the conformance of each idea to engineering requirements, 3) Variety – the dissimilarity of an idea within an individual's set of generated ideas, and 4) Novelty – the dissimilarity of an idea within the collectively exhaustive set of ideas.

With these metrics as a guide, an initial list of statements was developed using two approaches. First, literature was reviewed for statements that have been used to collect self-reported data on the four metrics. Second, the definitions of the four metrics from Shah and colleagues [3] were reviewed and converted to question form. This resulted in four statements per metric, totaling 16 statements.

Next, to assess question clarity regarding the four metrics and to ensure survey respondents accurately grasped the metric each statement pertained to, Latent Semantic Analysis (LSA) was employed to evaluate overlap. In addition, the statements were processed by a Large Language Model which was asked to assess overlap. Based on the findings from these analyses, the statements were modified to reduce overlap. A final verification of mutual exclusivity will be where participants are going to be asked to categorize each question into one of the four metrics.

The result of this work is a survey with statements which allows an individual to self-report their DSE tendency. In the future, this validity of self-reported data will be assessed by comparing it with direct assessment of DSE tendency. Once validated, the DSE survey is intended for researchers to gain a deeper understanding about DSE tendencies without having the resource-intensive, subjective task of performing direct assessments. Additionally, the survey can be used as a pre-screening if/when design exercises are deployed.

Introduction and Background

Engineering design is a systematic process that is used to develop solutions to problems that have multiple constraints. While there are many versions of the phases involved in engineering design [1], the fundamental stages are:

1. **Planning and Task Clarification**: This is the first step where detailed information about product requirements are collected, leading to the formulation of a requirements list. This list is pivotal in directing the design process and subsequent stages, necessitating frequent updates to accommodate ongoing changes and feedback.
2. **Conceptual Design**: The conceptual design phase involves abstracting key problems to define a principal solution, later made more specific through material and layout choices for assessment. This phase is crucial as it lays the foundation for the solution, with later phases focusing on refining and evaluating variants against technical and economic criteria before progressing to detailed embodiment design.

3. **Embodiment Design**: In the embodiment design phase, designers refine a technical system's structure from a basic concept, considering technical and economic criteria. Multiple preliminary layouts are compared to select the most promising one, which is further optimized. This final layout is subsequently used for functional and financial assessments before moving to the detailed design phase.
4. **Detailed Design and Documentation**: In the detailed design phase of product development, final decisions are made on part specifications, materials, production methods, and costs, leading to the creation of production documentation. This phase is crucial for refining design details and cost efficiency.

The design process is iterative and requires a team-based approach. Previous researchers have shown that the cost of making design changes increases ten-fold as one progress through the various stages of engineering design [2]. Therefore, it is critical that high effort is expended in the initial stages of design (in Task Clarification and in Conceptual Design).

The research presented in this paper focuses on the tendency of an individual to explore potential solutions during the Conceptual Design stage. The **design space** is defined as the set of ideas that are generated by an individual designer or group of designers to address an engineering problem space. The design space contains solutions which are projected to a performance space in which the behavioral performance of a solution is predicted [3]. Conceptual design is a stage where designers must employ divergent thinking and investigate as much of the design space as possible. An individual's tendency to survey the design space will henceforth be referred to in the context of **Design Space Exploration** (DSE).

Ideation Effectiveness and DSE in Conceptual Design

Previous research efforts from Shah and colleagues [3] identifies that ideation effectiveness can be measured by considering four outcome-based metrics:

- **Novelty** is a measure of how unexpected and unique an idea is in comparison with a reference group. Novelty is computed by collecting the ideas from all participants within a design ideation exercise, characterizing key attributes within the sample and finally counting the occurrence of those attributes. The attributes and characteristics with a lower count have a higher measure of novelty. Novel ideas occupy points in the design space that are not initially computed or have a lower probability of being developed by designers.
- **Variety** is a measure of a group of ideas. Variety is how different ideas are relative to each other and is computed in a pair-wise manner. The average variety of a group of ideas can be computed by averaging the pairwise variety of an idea. Variety is computed using a predetermined genealogy graph for each function with preassigned values.
- **Quality** is an evaluation of a single idea and is based on how well the idea will perform in accordance with evaluation criteria. These criteria may be generated from performance requirements, manufacturing, safety, or feasibility. The ability to evaluate and the uncertainty associated with quality is highly dependent on the phase of the design process.
- **Quantity** is the total number of ideas generated by an individual or group of participants within a design ideation exercise. Defining an idea can be subjective leading to

challenges in computing quantity. Quantity is determined by counting each of the documented ideas generated by participants.

These Shah-Vargas metrics will be referred to henceforth as the SV metrics. The research presented in this paper adopts these metrics to evaluate an individual's DSE tendencies.

The SV metrics have been used by several design researchers in creativity and ideation experiments. Refined scoring computations have been developed to evaluate idea generation effectiveness afforded by various methods. In these efforts, researchers typically conduct a design exercise where participants are required to perform concept generation. The concepts are then evaluated based on the four SV metrics and ideation effectiveness scores are generated. These evaluations are typically used to assess the effectiveness of treatments such as design-by-analogy approaches [4] and modes of communication during conceptual design [5]. Scoring is performed by multiple raters and is a resource-intensive, subjective process.

The research presented in this paper aims to develop a survey to be used as a suitable surrogate for completing a design study exercise. The former will yield results that are quantitative and hence analysis will be less subjective. The next section provides examples of design exercises from literature and elaborates on challenges with current methods of assessing DSE. The subsequent section details the development and evolution of the DSE survey. This is followed by conclusions and next steps.

Relevant Literature

The use of design exercises has been prevalent in engineering design literature as summarized by Kumar [6]. Hernandez and colleagues [7] used design exercises to evaluate the effectiveness of TRIZ over ad hoc ideation methods. Their research methodology involved conducting an identical design exercise at multiple universities and training raters to assess the concepts generated. The exercise involved three sessions and consumed nearly 3.5 hours of each participant's time. The authors noted that participants needed incentive (in their case – extra credit towards a course grade) to stay motivated throughout the exercise.

Toh and Miller [8] studied the utility of product dissection in the conceptual design stage. They recruited eight students to participate in a design exercise. They developed a 23-question survey for two raters to evaluate the concepts generated by the participants. The raters received training to ensure that they understood the intent of each of the 23 questions. The authors noted that consensus on the ratings was only reached after discussions.

Linsey and colleagues [5] compare four group ideation techniques and idea representation methods using SV metrics [3]. They incentivized ideation by offering participants extra credit based on quantity, quality, novelty, and variety of solutions developed. Once concepts were collected, a variety of techniques were employed to rate them. These involved binning ideas based on subjective assessment of similarity (for variety and novelty), evaluating concepts based on anchored scales for quality, and a three-criteria evaluation method for assessing quantity.

Another example of design exercises comes from Chan and colleagues [9]. These researchers investigated the effect of analogical distance on ideation effectiveness. They conduct a design exercise with a treatment group and a control group. They designed experimental protocols to minimize any difference during implementation of the exercise with the two groups. 153 participants were recruited by providing either monetary compensation or extra credit. Each participant spent 30 minutes on the design exercise. Evaluation of the 1321 concepts generated

was conducted in two stages. The first stage involved two trained coders who translated participants' work into solution concepts. Next, another set of raters evaluated the concepts for their relevance to the design problem presented. This resulted in a filtered list of 1066 concepts that were subsequently rated by one rater. A test-retest analysis was performed to assess the validity of the single rater's evaluation.

Summary of opportunities

A review of these works illuminates challenges associated with conducting and evaluating results from design exercises.

- Design exercises consume a significant amount of participant's time.
- Incentives (monetary, course grades) are needed to ensure sincere participation, which may still not be guaranteed.
- Conducting design exercises concurrently in multiple locations or replicating design exercises is difficult due to inherent (and unintentional) variations introduced by moderators.
- Evaluating concepts generated by participants is resource-intensive and subjective.
- Multiple raters are needed.
- High interrater agreement is required.
- If perfect agreement is needed, discussions among raters will also be needed.

To overcome these challenges, the research presented in this paper proposes a DSE survey that will replace DSE exercises.

Development of the DSE Survey

A four-step process was used to develop DSE survey statements. An overview of this process is shown in Figure 1, and results from each step are shown in Table 1 to Table 4. Details of each step are discussed in the remainder of this section.

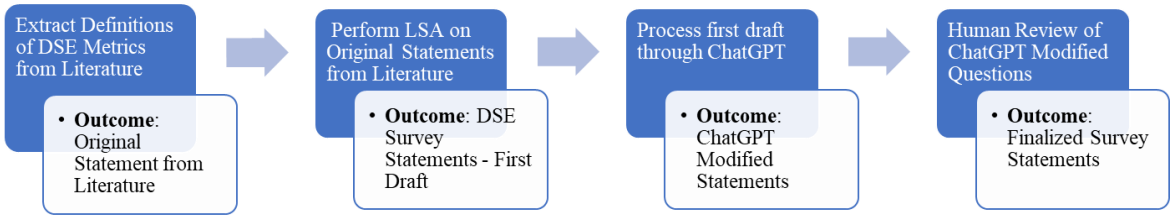

Figure 1: Process for Development of DSE Survey Statements

Step 1: Extract Definitions of DSE Metrics from Literature

The DSE survey statements are derived from three primary sources [3], [10], [11]. Although different, creativity and DSE share foundational concepts. Carroll [12]develops a standardized measurement tool to evaluate creativity support tools. The study uses seven statements from the International Personality Item Pool (IPIP) [11] to provide a standardized measure of the participant's creativity levels. The seven statements presented in the literature are strongly

correlated with the SV metrics of Novelty and Variety. Further exploration of the IPIP, beyond the seven statements from Carroll [12] was performed. Specifically, phrases in the Creativity/Originality category were analyzed for relevance to the DSE and Shah's definitions of ideation effectiveness metrics.

Oman and colleagues [10] refer to the SV metrics [3] to quantify concept design by mechanical engineering students. The researchers adapted these metrics to present a modified definition of Novelty, Variety, Quantity, and Quality. Research from Oman and colleagues [10], and items from the IPIP [11] were adapted considering SV metrics of ideation effectiveness. This resulted in the sixteen original DSE statements (see the first column in Table 1 to Table 4).

Table 1. Development of novelty-focused statements for survey. Original statements extracted from [11]

Original statement from literature	DSE Survey Statements – First Draft	ChatGPT modified statements	Final statements for survey use
Have recently found an original solution to a problem in my life.	I am recognized for having unexpected and unusual ideas.	I am known for consistently presenting unexpected and unconventional ideas.	I am recognized for consistently presenting unexpected and unusual ideas
	I tend to mostly have usual and conventional ideas	While my tendencies lean towards conventional thinking, I'm actively cultivating a penchant for more unexpected ideas	I tend to generally produce conventional ideas
Don’t pride myself on being original.	I take pride in producing ideas that are unusual and nontraditional compared to the norm	I strongly value producing ideas that break away from traditional norms and conventions.	I take pride in coming up with concepts that are out of the ordinary and unconventional compared to the norm.
	I find it difficult to produce ideas that are unusual and unexpected.	I sometimes encounter challenges when attempting to generate ideas that are unexpected and out of the ordinary.	I find it difficult to produce solutions that are unconventional.

Table 2. Development of variety-focused statements for survey. Original statements extracted from [11]

Original statement from literature	DSE Survey Statements – First Draft	ChatGPT modified statements	Final statements for survey use
Come up with alternatives	I tend to think of alternative solutions to one problem	I naturally explore various alternative solutions when faced with a problem.	I naturally explore various alternative solutions when faced with a problem.
	I struggle with coming up with alternative solutions to a single problem.	While I sometimes struggle, I believe in the importance of generating multiple solutions for a single problem.	I struggle with coming up with alternative solutions to a single problem.

Original statement from literature	DSE Survey Statements – First Draft	ChatGPT modified statements	Final statements for survey use
Enjoy hearing new ideas	I value hearing different viewpoints during brainstorming sessions to acquire ideas for my own solutions to a problem.	I highly value diverse viewpoints during brainstorming to explore a wider spectrum of potential solutions.	I highly value hearing multiple viewpoints during brainstorming to explore a wider spectrum of potential solutions.
	I find it most effective to develop my solutions to a problem independently, without seeking input from multiple people.	While I often work independently, I recognize the value of others' input in exploring a broader range of possibilities.	I find it most effective to develop my solutions to a problem independently, without seeking input from multiple people.

Table 3. Development of quantity-focused statements for survey. Original statement extracted from [10]

Original statement from literature	DSE Survey Statements – First Draft	ChatGPT modified statements	Final statements for survey use
Quantity is simply the total number of ideas under the assumption that the more ideas there are the greater the chance of creating innovative solutions	I believe that it is critical to generate a large number of ideas.	I firmly believe that generating a larger quantity of ideas increases the chances of finding valuable solutions.	I firmly believe that generating a larger quantity of ideas increases the chances of finding valuable solutions.
	Limiting the number of ideas reduces the likelihood of generating a better idea	I hold the view that constraining the number of ideas might hinder the potential for discovering innovative solutions.	I believe that reducing the amount of solutions helps me identify the best one.
	I typically generate a large number of ideas when brainstorming for solutions	When brainstorming for solutions, I tend to produce a substantial number of ideas.	When brainstorming for solutions, I tend to produce a large number of solutions.

Original statement from literature	DSE Survey Statements – First Draft	ChatGPT modified statements	Final statements for survey use
	I frequently struggle to generate a large number of solutions when brainstorming	I often face challenges in generating a significant number of solutions during brainstorming sessions.	I frequently struggle to generate a large number of solutions when brainstorming

Table 4. Development of quality-focused statements for survey. Original statement extracted from [10]

Original statement from literature	DSE Survey Statements – First Draft	ChatGPT modified statements	Final statements for survey use
Quality measure how feasible the set of ideas is as well as their relative ability to satisfy Design requirements	When brainstorming I often do thorough research to make sure my solution meets the design requirements	During brainstorming, I frequently conduct thorough research to ensure my solution aligns with design requirements.	When brainstorming I often do thorough research to make sure my solution meets the design requirements.
	During the brainstorming process for solutions I tend use my own intuition instead of relying on research to meet design requirements	When brainstorming solutions, I often rely on my intuition rather than extensive research, while keeping design requirements in mind.	I tend to use my own intuition instead of relying on research to meet design requirements.
	I frequently come close to satisfying the design requirements when forming concepts.	Forming concepts that closely adhere to design requirements is a frequent outcome of my brainstorming sessions.	Forming concepts that closely adhere to design requirements is a frequent outcome of my brainstorming sessions.
	I find it challenging to develop concepts that fully meet the design requirements.	I find it a bit challenging to consistently develop concepts that perfectly align with all design requirements.	I find it challenging to develop concepts that fully meet the design requirements.

Step 2: Perform Latent Semantic Analysis on Original Statements from Literature

Latent Semantic Analysis [13] was used to compare the sixteen statements to definitions of the four ideation effectiveness metrics. This resulted in a 16x4 matrix where the number in each cell is the cosine similarity score between a question and the definition of a metric. Table 5 shows this matrix, and as an example, the LSA cosine similarity between "I tend to think of alternative solutions to one problem" and "wide range of possible solutions for a single problem" (the definition of Variety) is 0.72. The DSE metrics and associated textual definitions are:

- Novelty {Nov} unusual and unexpected
- Variety{Var} wide range of possible solutions for a single problem
- Quality{Qly} feasible and comes close to meeting design requirements
- Quantity{Qnt} large number of solutions

Table 5: Latent Semantic Analysis Scores for DSE Survey Statements - First Draft

	DSE Metric Definition			
DSE Survey Statements – First Draft	**Nov**	**Var**	**Qly**	**Qnt**
I am recognized for having unexpected and unusual ideas	0.51	0.37	0.46	0.25
I tend to mostly have usual and conventional ideas	0.53	0.43	0.53	0.32
I take pride in producing ideas that are unusual and nontraditional compared to the norm	0.6	0.51	0.59	0.39
I find it difficult to produce ideas that are unusual and unexpected.	0.62	0.54	0.6	0.41
I tend to think of alternative solutions to one problem	0.48	0.72	0.48	0.49
I struggle with coming up with alternative solutions to a single problem.	0.5	0.74	0.53	0.5
I value hearing different viewpoints during brainstorming sessions to acquire ideas for my own solutions to a problem.	0.53	0.63	0.54	0.45
I find it most effective to develop my solutions to a problem independently, without seeking input from multiple people.	0.55	0.67	0.6	0.48
When brainstorming I often do thorough research to make sure my solution meets the design requirements	0.51	0.58	0.63	0.45
During the brainstorming process for solutions I tend use my own intuition instead of relying on research to meet design requirements	0.55	0.61	0.7	0.47
I frequently come close to satisfying the design requirements when forming concepts.	0.52	0.5	0.73	0.36
I find it challenging to develop concepts that fully meet the design requirements.	0.51	0.51	0.71	0.36
I believe that it is critical to generate a large number of ideas.	0.54	0.53	0.59	0.61
Limiting the number of ideas reduces the likelihood of generating a better idea	0.42	0.48	0.48	0.59

	DSE Metric Definition			
DSE Survey Statements – First Draft	**Nov**	**Var**	**Qly**	**Qnt**
I typically generate a large number of ideas when brainstorming for solutions	0.52	0.63	0.57	0.72
I frequently struggle to generate a large number of solutions when brainstorming	0.52	0.64	0.57	0.75

In this matrix, the highest score for a row is highlighted to show that in all but one case, statements are most semantically similar to only one ideation effectiveness metric. However, the numerical difference between the highest score and second-highest score is not numerically significant. In many cases, this difference is less than 2%. It is likely that the embedding space ("General Reading up to 1st year college") has an impact on the cosine scores generated. To mitigate this issue, a Large Language Model (LLM) [14] was used to assess semantic similarity between statements and metric definitions.

Step 3: Process First-Draft through ChatGPT

The second NLP approach used to evaluate the question orthogonality was based on the LLM encoded in ChatGPT [14]. The 16 DSE statements and four DSE definition were entered to ChatGPT 3.5. ChatGPT was prompted to categorize the statements based on the four metrics. The results are presented in Table 6.

Table 6: Comparing assessments provided by LSA and ChatGPT

Legend: Numerical value = LSA score; o = Category based on LSA; ✓ = Category based on ChatGPT

	Nov	**Var**	**Qly**	**Qnt**
I am recognized for having unexpected and unusual ideas.	**0.51 (o ✓)**	**0.37 ( )**	**0.46 ( )**	**0.25 ( )**
I tend to mostly have usual and conventional ideas.	**0.53 (o ✓)**	0.43 ( )	0.53 (o)	0.32 ( )
I take pride in producing ideas that are unusual and nontraditional compared to the norm.	**0.6 (o ✓)**	0.51 ( )	0.59 ( )	0.39 ( )
I find it difficult to produce ideas that are unusual and unexpected.	**0.62 (o ✓)**	0.54 ( )	0.6 ( )	0.41 ( )
I tend to think of alternative solutions to one problem.	0.48 ( )	**0.72 (o ✓)**	0.48 ( )	0.49 ( )
I struggle with coming up with alternative solutions to a single problem.	0.5 ( )	**0.74 (o ✓)**	0.53 ( )	0.5 ( )
I value hearing different viewpoints during brainstorming sessions to	0.53 ( )	0.63 (o)	0.54 ( )	0.45 (✓)

Legend: Numerical value = LSA score; o = Category based on LSA; ✓ = Category based on ChatGPT

	Nov	Var	Qly	Qnt
acquire ideas for my own solutions to a problem.				
I find it most effective to develop my solutions to a problem independently, without seeking input from multiple people.	0.55 ( )	0.67 (o)	0.6 ( )	0.48 (✓)
I often do thorough research to make sure my solution meets the design requirements.	0.51 ( )	0.58 ( )	**0.63 (o ✓)**	0.45 ( )
I tend use my own intuition instead of relying on research to meet design requirements.	0.55 ( )	0.61 ( )	**0.7 (o ✓)**	0.47 ( )
I frequently come close to satisfying the design requirements when forming concepts.	0.52 ( )	0.5 ( )	0.73 (o)	0.36 (✓)
I find it challenging to develop concepts that fully meet the design requirements.	0.51 ( )	0.51 ( )	**0.71 (o ✓)**	0.36 ( )
I believe that it is critical to generate a large number of ideas.	0.54 ( )	0.53 ( )	0.59 ( )	**0.61 (o ✓)**
Limiting the number of ideas reduces the likelihood of generating a better idea	0.42 ( )	0.48 ( )	0.48 ( )	**0.59 (o ✓)**
I typically generate a large number of ideas when brainstorming for solutions	0.52 ( )	0.63 ( )	0.57 ( )	**0.72 (o ✓)**
I frequently struggle to generate a large number of solutions when brainstorming	0.52 ( )	0.64 ( )	0.57 ( )	**0.75 (o ✓)**

In some instances, there is disagreement between LSA and LLM. Therefore, ChatGPT was asked to modify the 16 statements to ensure mutual exclusivity between metrics. This resulted in the 16 statements listed in Table 1 to Table 4 under the column "ChatGPT modified statements."

Step 4: Human Review of ChatGPT Modified Questions

A human review of the ChatGPT statements was conducted and the statements were modified for ease of comprehension. This revised version of the 16 survey statements is shown in Table 1 to Table 4 under the "Final statements for survey use" column. These 16 DSE survey statements will each be associated with a 5-point Likert scale.

Conclusions and Next Steps

The research presented in this paper is a step toward a survey for assessing individual DSE tendencies. The survey is intended to support design researchers on two levels. The first level is the DSE survey serving as a suitable replacement for design ideation exercises. Second, the DSE survey may be used as a pre-screening to understand an individual's DSE tendencies before they perform an ideation exercise. The design of the survey statements is an important task and have been derived from common literature in engineering design creativity and ideation and the more general set of IPIP statements. The primary contribution from this research is synthesizing a set of questions that are orthogonally related to the ideation metrics. The question orthogonality is analyzed using a combination of NLP (LSA, LLM) and human interpretation. This has resulted in a 16-question survey containing four survey statements each for Novelty, Variety, Quality, and Quantity.

Future work includes verifying that the mutual exclusivity gained by processing the survey statements through NLP techniques concurs with human interpretation of the survey statements. This will be done by conducting a survey where participants are asked to categorize each question into relevant SV metrics.

In addition to the validation of mutual exclusivity, the survey statements may need to be reframed to solicit responses based on recent experiences. As stated, the survey statements are general and invoke a large timeframe's retrospection.

A critical next step involves deploying the DSE survey concurrently with a design exercise. This will allow for results from the two to be studied for any correlations and underlying causalities. If causalities are found, then the DSE survey can be used instead of design exercises moving forward. Since deployment, completion, and analysis of results of the DSE survey involve less effort than that of a design exercise, the former can be deployed widely. The analysis of results will be more objective too. If valid, the DSE survey will be a tool that researchers can use to understand DSE ability of large groups of people without having the resource-intensive, subjective task of performing direct assessments.

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