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Work in Progress: Do Students Really Understand Design Constraints? A Baseline Study

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Dr. Estell is active in the assessment community with his work in streamlining and standardizing the outcomes assessment process, and has been an invited presenter at the ABET Symposium. He is also active within the engineering education community, having served ASEE as an officer in the Computers in Education and First-Year Programs Divisions; he and his co-authors have received multiple Best Paper awards at the ASEE Annual Conference. His current research includes examining the nature of constraints in engineering design and providing service learning opportunities for first-year programming students through various K-12 educational activities. Dr. Estell is a Member-at-Large of the Executive Committee for the Computing Accreditation Commission of ABET, and also serves as a program evaluator for the Engineering Accreditation Commission. He is also a founding member and serves as Vice President of The Pledge of the Computing Professional, an organization dedicated to the promotion of ethics in the computing professions through a standardized rite-of-passage ceremony.

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Introduction

First-year engineering programs often include a design project within the curriculum. The introduction of the design project meets goals often mentioned in these programs: experiencing an engineering design process, incorporating some amount of hands-on experience (typically with a lower-fidelity proof of concept or prototype), and demonstrating that a design can meet the needs and specifications of some customer. These designs, like those in the "real world," are constrained in many ways and must meet suitable evaluation metrics (the criteria against which various design options are considered relative to desired needs and specifications) to demonstrate their success at an acceptable level. However, the discussion of evaluation metrics and constraints is often limited in the first year curriculum, being covered near the beginning of the design process, and then no longer discussed until the requirement validation phase; this can lead to a lack of appreciation for the consideration of realistic evaluation metrics and constraints through the various stages of the design process.

A broader research effort is underway to develop a more robust and meaningful pedagogical approach towards realistic constraints, particularly in their introduction within the first year of engineering coursework. The goals for this research are that, by categorizing constraints such that the source of a constraint is also included, an engineering student can (1) examine each design attribute from the point of view of a stakeholder from that source area, thereby allowing for a greater perspective on how such attributes can constrain the design, and (2) gain an appreciation for the general education courses that provide these perspectives. This paper seeks to explore the early stages of this development effort. Specifically, it introduces the approach itself, discusses an initial classroom application, and examines preliminary data regarding instructor consistency in assessment of the tool. Preliminary analysis is also reported regarding a comparison of response data from novice, advanced beginner, and expert users.

ABET and Realistic Constraints

Under the proposed changes to the Engineering Criteria, ABET defines engineering design as:

> *"[T]he process of devising a system, component, or process to meet desired needs and specifications* ***within constraints*** *[emphasis added]. It is an iterative, creative, decision-making process in which the basic sciences, mathematics, and engineering sciences are applied to convert resources into solutions. The process involves identifying opportunities, performing analysis and synthesis, generating multiple solutions, evaluating those solutions against requirements, considering risks, and making trade-offs to identify a high quality solution under the given circumstances."*[1]

ABET then goes on to explain, "for illustrative purposes only," that the following items constitute examples of possible constraints: accessibility, aesthetics, constructability, cost, ergonomics, functionality, interoperability, legal considerations, maintainability, manufacturability, policy, regulations, schedule, sustainability, and usability. Unfortunately, it has been too often the case that students – and sometimes, instructors – have treated the contents of the list of eight constraints currently presented in Criterion 3(c) (economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability) as being exhaustive. Additionally, as these constraints are not well defined, even within textbooks on engineering design, various interpretations as to what these constraints constitute often come into play, some of which are not always found to be valid by a visiting ABET program evaluator.

On Design

> *"Design is the practice of intentional creation to enhance the world. It is a field of doing and making, creating great products and services that fit human needs, that delight and inform. Design is exciting because it calls upon the arts and humanities, the social, physical, and biological sciences, engineering and business."*
>
> – Don Norman, "State of Design: How Design Education Must Change"[2]

Anyone can design a product, yet good design involves making a product both useful and understandable. Design is more than just the application of technology: because products interact with people at several levels, it can be stated that design encompasses the human condition. Accordingly, to become effective at design, one must at least become familiar with the various aspects of the human condition as experienced through the study of the humanities, thereby necessitating an understanding of pertinent concepts emanating from the social, behavioral, and biological sciences.

Once designed, a product needs to be built, and in many cases, marketed. Designers must understand the critical roles that both engineering and business play in seeing a design through fruition, either delivered to the client or available in the marketplace, and accepted by stakeholders.

To be quality designers, engineering students require a broad-based education, grounded not only in STEM (science, technology, engineering, and math) related topics, but also in liberal arts and business. This, therefore, is the underlying rationale for engineering majors to take general education courses, and is best expressed by the following quotes: first, from Dieter Rams, the famed head of design for the German company Braun:

> *"You cannot understand design if you do not understand people; design is made for people."*[3]

and from Steve Jobs, co-founder of Apple:

> *"It's in Apple's DNA that technology alone is not enough – that it's technology married with liberal arts, married with the humanities that yields us the result that makes our heart sing."*[4]

The Constraint-Source Model

The Constraint-Source Model (CSM) for engineering design builds upon the views of Steve Jobs, Don Norman, and Dieter Rams by assuming that the constraints affecting a design can be modeled as being attributes derived from one of four possible source classification areas:

business-driven, customer-driven, societal, and technical.[5] The CSM is conceptually based on the four characteristics of the entrepreneurial engineer as identified in 2010 by the Kern Engineering Entrepreneurship Network:[6]

- An understanding of the *technical* fundamentals of engineering,
- An understanding of *customers*,
- An understanding of *business* to support the organizations in which they work, and
- An understanding of *societal* values.

Under the CSM, all engineering designs contain a set of *attributes*, identified through the design process, that are used to describe various parameters associated with the design, most notably the evaluation metrics and the constraints. *Evaluation Metrics* are those attributes upon which specifications are placed to help achieve a client's needs. These evaluation metrics are then used to evaluate proposed designs, often with comparisons to benchmarks, to determine the extent to which a particular design meets those desired needs. *Constraints* are the attributes upon which noticeable, realistic limitations have been placed due to externally-sourced influences. While serving as boundaries limiting design freedom, the set of constraints associated with a project has the effect of eliminating those designs that would fail, thereby allowing designers to focus on designs that might succeed. Figure 1 presents a visual representation of these key CSM terms.

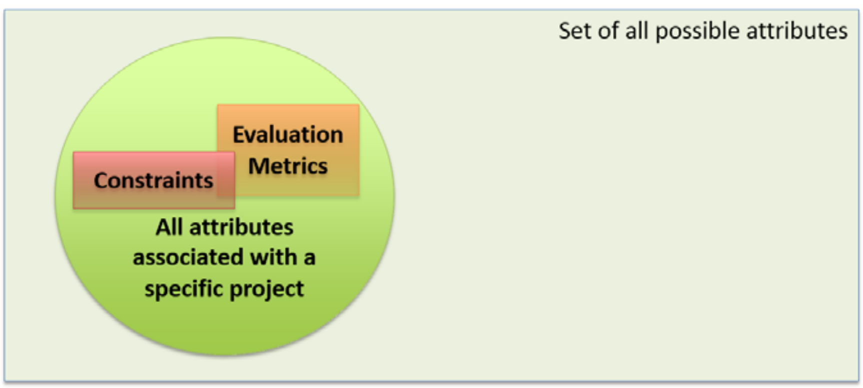

FIGURE 1: RELATIONSHIP VISUALIZATION OF THE CONSTRAINT-SOURCE MODEL

Note that an attribute can be both a constraint and an evaluation metric, as indicated by the overlap shown in Figure 1. For example, consider a ship's size: although Panamax-compliant ships cannot exceed the dimensions of a lock on the Panama Canal (a constraint), Iowa-class battleships were designed for maximum size capacity (an evaluation metric) while within appropriate dimensions to pass through the canal.

Setting and Purpose

The primary study population (N_F = 96 respondents) consists of students enrolled in a first semester interdisciplinary Introduction to Engineering course at Ohio Northern University, a small private university in the Midwest. The student population includes international and underrepresented minority students, but is largely made up of those from small, rural towns. All students in the College of Engineering (except for computer science majors) are required to take the Introduction to Engineering course. The focus of this course is on the engineering design cycle, including the introduction of constraints in a design context.

Two comparison groups, also affiliated with the college, are being used. The first group consists of seniors enrolled in a first semester capstone design course (N_S = 19 respondents), all of whom have already completed the Introduction to Engineering course. The second group consists of practicing engineers pulled from the college's industrial advisory board, program working groups, and alumni population (N_P = 12 respondents).

The purpose of this study is to evaluate the Constraint-Source Model as a tool for exposing students to potential sources of design constraints and to evaluate how engineers at various levels use the tool to perform constraint analysis. The CSM provides eliciting quantitative and qualitative questions for a set of over 40 commonly experienced design attributes, allowing one to categorize the level to which each attribute serves to constrain the solution space for the problem being addressed. For this research, a subset of 15 design attributes was used, so as to not overwhelm the first-year students. By comparing and contrasting the responses received from the three study groups, it is hypothesized that an initial set of gaps and misconceptions can successfully be identified. It is further hypothesized that the CSM will serve as a useful tool for instructors to evaluate student thinking in the area of design constraints.

The Constraint-Source Model: Examples

In its current state, the Constraint-Source Model presents specifics of design attributes from a particular source area and how they might constrain a design by using a short definition followed by one or more examples. Additionally, misconceptions are sometimes listed to serve as counter-examples for those attributes that are often misidentified. Two sample constraint sources from the CSM are provided below in Figure 2; these examples are significant as they collectively underscore how the parameters of an ABET-listed example Criterion 3(c) constraint, environmental, can change depending upon a stakeholder's point of view.

Environmental-Technical Constraints:
A technically-derived environmental constraint occurs when the environment might have a potentially negative impact on the product, thereby affecting the design of the product.

Examples:

- Designing a shoe – what is the functional purpose of that shoe? If the purpose is for winter hunting, a designer would want to include appropriate traction with the sole, ankle support, and insulation; a standard dress shoe would provide none of these.
- Water-resistant watches commonly have an O-ring type seal behind the battery access panel to protect the electronics inside.

Environmental-Societal Constraints:
Societally-derived environmental constraints occur when the product must be designed to avoid a potentially negative impact on the environment.

Example:

- Cars were once designed to operate with leaded gasoline (using tetraethyl lead as an additive) to inexpensively serve as an antiknock agent and to both increase power and fuel economy; unfortunately, this design decision placed lead, a now known neurotoxin, into the environment. Removal of lead additives required an engine redesign to avoid engine knock.

Misconceptions:

- Students often present generalizations that a product needs to be designed such that it doesn't pollute, that it can be recycled, etc., without specifically tying these points back to the product requirements.

FIGURE 2. EXAMPLES OF CONSTRAINT-SOURCE MODEL DESIGN ATTRIBUTES.

The design attributes currently listed as typical potential constraints in the CSM are shown in Table 1. These attributes are not meant to serve as an exhaustive list, but as a convenient starting point for performing a constraint analysis for a given problem. Note that each source has an associated code for ease of identification and reference during later analysis.

TABLE 1: ATTRIBUTES IDENTIFIED AS TYPICAL CONSTRAINTS IDENTIFIED IN THE CSM, GROUPED BY SOURCE CLASSIFICATION AREA

	Code	***Attribute***
Society-Driven	S-1.	Affordability
	S-2.	Customs/Traditions
	S-3.	Environmental
	S-4.	Health
	S-5.	Manufacturability
	S-6.	Policy
	S-7.	Regulatory
	S-8.	Safety
	S-9.	Sustainability

	Code	***Attribute***
Business-Driven	B-1.	Competition
	B-2.	Ethical
	B-3.	Labor
	B-4.	Liability
	B-5.	Manufacturability
	B-6.	Regulatory
	B-7.	Schedule
	B-8.	Supply Chain
	B-9.	Sustainability

	Code	***Attribute***
Technically-Driven	T-1.	Accuracy
	T-2.	Capacity
	T-3.	Electrical
	T-4.	Environmental
	T-5.	Manufacturability
	T-6.	Mechanical
	T-7.	Physical
	T-8.	Precision
	T-9.	Reliability
	T-10.	Size
	T-11.	Thermal

	Code	***Attribute***
Customer-Driven	C-1.	Accessibility
	C-2.	Aesthetics
	C-3.	Efficiency
	C-4.	Ergonomic
	C-5.	Health
	C-6.	Learnability
	C-7.	Maintainability
	C-8.	Physical
	C-9.	Risks
	C-10.	Safety

When students are asked to analyze the design space for a particular problem, they are presented with the list of attributes in Table 1 in a format similar to that shown in Figure 3.

	Definitely	**Probably**	**Maybe**	**Probably Not**	**Definitely Not**	
B-1	☒	☐	☐	☐	☐	**[Competition] Does the product need to sufficiently differentiate itself from the competition in order to achieve an acceptable market share?** There are many similar products that are already on the market. In order to have a successful crowdfunding campaign, our product needs to differentiate itself to get people to fund our project versus buying a product already on the market.

FIGURE 3. EXAMPLE OF AN ANSWERED CONSTRAINT-SOURCE MODEL QUESTION.

The design attributes are grouped into sections, as indicated in Table 1. Within its section, each attribute is listed with an eliciting, reflective question. Students are asked to respond both quantitatively and qualitatively. On the quantitative side, the CSM provides the following five possible responses for classifying the degree to which they believe that the attribute under consideration constrains the design space of the problem, from the point of view of the source:

1. **Definitely Not –** the attribute does not play a role in the design or does play a role but is clearly not constrained.
2. **Probably Not –** while the attribute does or could possibly play a role in the design, the attribute is either not constrained by external influences or the constraints associated with other attributes relegates the attribute to a non-primary role.
3. **Maybe –** a possibility exists that the attribute is present in the design and might be affected by an identifiable external influence; accordingly, the question requires further research.
4. **Probably –** the attribute plays a role in the design, plus it is likely, to the extent that one cannot rule out the possibility, that the attribute is affected by an identifiable external influence; accordingly, the question requires appropriate research.
5. **Definitely –** the attribute plays a clear role in the design, plus there is an identifiable, external influence that requires a realistic limitation to be placed upon the attribute.

For the qualitative response, students are asked to briefly justify their quantitative response. As an example, Figure 3 includes a student response for a problem where the design team was asked to consider the development of a product that serve as a multicolored illumination base for a translucent item such as a paperweight or a wine bottle.

Data Collection and Analysis Methodology

Participants in the study were presented with a problem of someone wanting an easier way to haul things in and out of an existing household attic, along with instructions for using the Constraint-Source Model to perform the constraint analysis. The exact prompt given to participants was as follows:

> *All of the materials for celebrating the Christmas holidays in the Smith household are stored in the attic above the garage, which is only accessible through a pull-down ladder* (Figure 4). *Can something be designed to solve this problem so Mr. Smith doesn't have to carry all of these materials – boxes, tree branches, plastic Santas and snowmen, etc., up and down the stairs? Perhaps others find this to be a problem as well – perhaps a commercial product could be developed!*

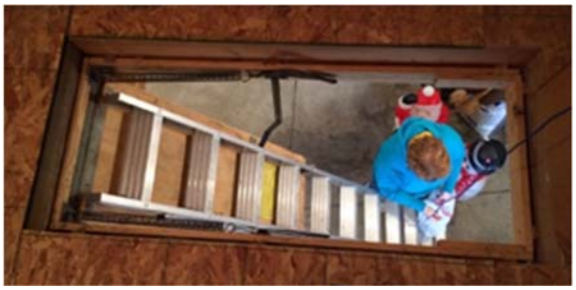

FIGURE 4: VIEW FROM GARAGE ATTIC

In all cases, the CSM was administered via a web-based Google Form to allow ease of data collection and analysis. All data was collected in an anonymous format, with separate forms distributed to each study population to allow differentiation between the groups. First-year students were assigned completion of the activity as part of a regular homework assignment. Participation from other populations was strictly voluntary, solicited via college email lists and social media groups.

While each constraint source has been fully defined in the CSM, complete with examples and, in most cases, common misconceptions (as illustrated in the previous section), providing this level of detail in the survey was deemed overwhelming for first-year students, and therefore impractical. Instead, participants were asked to answer the following subset of CSM questions relative to the scenario, listed in Table 2.

TABLE 2: CSM SURVEY QUESTION DETAILS

Classification Area	***Code***	***Attribute***	***Survey Question***
Technically-Driven	T-1	Accuracy	Is it sufficiently important that the measured value of a manufactured component used in the design be close enough to its expected value that you are willing to pay more to ensure that desired level of closeness for that component?
	T-2	Capacity	Will the product be affected by either a minimum or maximum capacity requirement when in regular use?
	T-4	Environmental	Can the operational environment negatively impact the product through normal use?
	T-10	Size	Must the size of the product, in one or more dimensions, be limited by either a minimum or a maximum value in order to ensure its envisioned use?
Customer-Driven	C-2	Aesthetics	Is it necessary that the design makes the product appealing (e.g., through color, form, sound, texture) to the customer?
	C-4	Ergonomic	Is it essential that the design accommodate the physiological needs of the customer to either provide optimum comfort and/or to avoid injury?
	C-6	Learnability	Is it essential that the design allow someone to successfully accomplish basic tasks the first time they use this type of product?
	C-10	Safety	Is it possible for a customer to suffer harm through the ordinary use (or accidental misuse) of this type of product?
Societal-Driven	S-1	Affordability	Is it necessary that the product can be purchased (initial cost) and used (recurring cost) at a total cost that is within the financial means of a typical member of the targeted customer group?
	S-3	Environmental	Is it probable that the regular use of this type of product might have a potentially negative impact on the environment?
	S-7	Regulatory	Are there any laws at the local, regional, and/or national level that this type of product must comply with?
	S-8	Safety	Might members of the customer’s immediate and/or wider community suffer harm through the ordinary use (or accidental misuse) of this type of product?
Business-Driven	B-1	Competition	Does the product need to sufficiently differentiate itself from the competition in order to achieve an acceptable market share?
	B-6	Regulatory	Are there any industrial standards for which the product, or some component of the product, must comply with?
	B-9	Sustainability	Will the design require the use of raw materials that might not be obtainable in sufficient quantities over the expected production lifetime of the product?

A group of four instructors, all current or former instructors of the Introduction to Engineering course, were given survey responses for evaluation. In the case of the senior and practitioner groups, the entire study population was used for analysis. In the case of the first-year group, a subset of 30 responses was used for analysis. Although there is no fixed rule for an appropriate sample size in such qualitative work, 20-30 samples is generally regarded as sufficient to achieve data saturation in most populations.[7] For all three populations the same subset of four CSM attributes were selected for analysis. Environmental-Technical (T-4) and Competition-Business (B-1) were selected based on the expectation that novice users would be able to fully understand the nature of the attribute and that higher quality responses would be observed. The two Safety attributes from the Customer and Societal (C-10 and S-8) classification areas were selected based on the opposite expectation: that novice users would struggle to differentiate the two attributes and lower quality responses would be observed. The motivation behind using a subset of data, rather than the entire population, was to alleviate the time burden on reviewing faculty members. A more complete analysis will be performed in future phases of this study.

Evaluators were asked to rate each response on three metrics: Depth of Thought, Validity of Argument, and Degree of Relevance. Depth of Thought is defined as the extent to which the response showed consideration and/or reflection upon how the attribute can affect the design space; validity of the response was not a consideration in this determination. Validity of Argument was defined as the extent to which the response provided appropriate reasons for accepting the conclusion indicated by the selected classification; clarity or depth of the response was not a consideration in this determination. Degree of Relevance was defined as the extent to which the response accurately addressed both the problem and attribute under consideration. The three metrics were rated on a three-point scale, ranging from Low/Weak (1) to High/Strong (3). Rubrics for each of the three are included below as Tables 3-5. Additional examples of each rubric level were provided to the evaluators but are omitted below.

TABLE 3: EVALUATION RUBRIC FOR DEPTH OF THOUGHT

Depth of Thought		
Low/Weak	Medium	High/Strong
1. Response demonstrates either a lack of reflection on the attribute in question, or a minimal amount of reflection upon how the attribute potentially affects the design space. 2. Response employs “black or white” thinking and avoids the potential complexities involved. Example: (Safety, Definitely) The product should be very safe.	3. Response indicates some thought but does not fully explore the concept. 4. Response presents reflections regarding the attribute that are supported, but lack insight. Example: (Safety, Definitely) This product, if misused and mistreated, has the potential to severely injure the consumer.	5. Response is clear and indicates careful consideration of the prompt. 6. Response presents reflections regarding the attribute that are insightful and well supported. Example: (Safety, Definitely) This can relate to bad reputations, lawsuits/legal troubles, and protests against the use of the product if the customer gets injured. Warning labels and instructions should definitely be included with the product.

TABLE 4: EVALUATION RUBRIC FOR VALIDITY OF ARGUMENT

Validity of Argument		
Low/Weak	Medium	High/Strong
1. Response is incorrect, illogical, or restates what is obvious. 2. Arguments and assumptions are flawed, unsupported, or unjustified. Example: (Size, Probably Not) No matter what the size is, the functions of the product would not change.	3. Response is poorly supported or uses questionable logic. 4. Response only partially justifies assumptions used to make the classification. Example: (Size, Probably) The size of the objects being moved can range from smaller to large heavy packages.	5. Response makes a logical and valid argument for its position. 6. Response clearly identifies and justifies assumptions used to make the classification. Example: (Size, Probably) Yes, because a product can't be too large or it becomes cumbersome and impractical for its intended use.

TABLE 5: EVALUATION RUBRIC FOR DEGREE OF RELEVANCE

Degree of Relevance		
Low/Weak	Medium	High/Strong
1. Response indicates a clear lack of understanding of the attribute or lacks focus. 2. Key questions regarding the attribute's impact on the design space are either misidentified or not identified. Example: (Competition, Probably Not) As long as the product is functional and efficient.	3. Response indicates some misunderstanding of the attribute or focus is somewhat unclear or cluttered. 4. Key questions regarding the attribute's impact on the design space are partially identified but not necessarily contextually explained. Example: (Competition, Maybe) Sometimes, the best products travel by word of mouth and can only truly stand out through use by customers.	5. Response demonstrates an understanding of the attribute in question and stays on topic. 6. Key questions regarding the attribute's impact on the design space are identified and contextually explained. Example: (Competition, Definitely) Your product should stand out or compete with the other best products in order for more people to purchase it.

Discussion of First-Year Student Perceptions

At the end of the semester, first-year students were asked to complete an anonymous survey regarding various aspects of the Introduction to Engineering course; four questions were asked regarding the utility of the CSM. Students were asked to indicate their level of agreement with the following prompts using a five-point scale (Strongly Agree, Somewhat Agree, Neither Agree nor Disagree, Somewhat Disagree, Strongly Disagree):

Q1. The model is useful for identifying criteria and constraints
Q2. The model is easy to use
Q3. The model is difficult to understand
Q4. I will use the model again on future design problems

Aggregate student response data is included in Figure 5. Most students responded positively (Strongly or Somewhat Agree) that the CSM is both useful and easy to use. Question 3, regarding difficulty of understanding, was designed as an inverted question and most students responded in the negative (*i.e.*, not difficult to understand). Almost all students were at least open to the idea of using the CSM again in the future. These results are reassuring and affirm that the Constraint-Source Model, once fully developed, will be a useful tool for student generation of evaluation metrics and constraints.

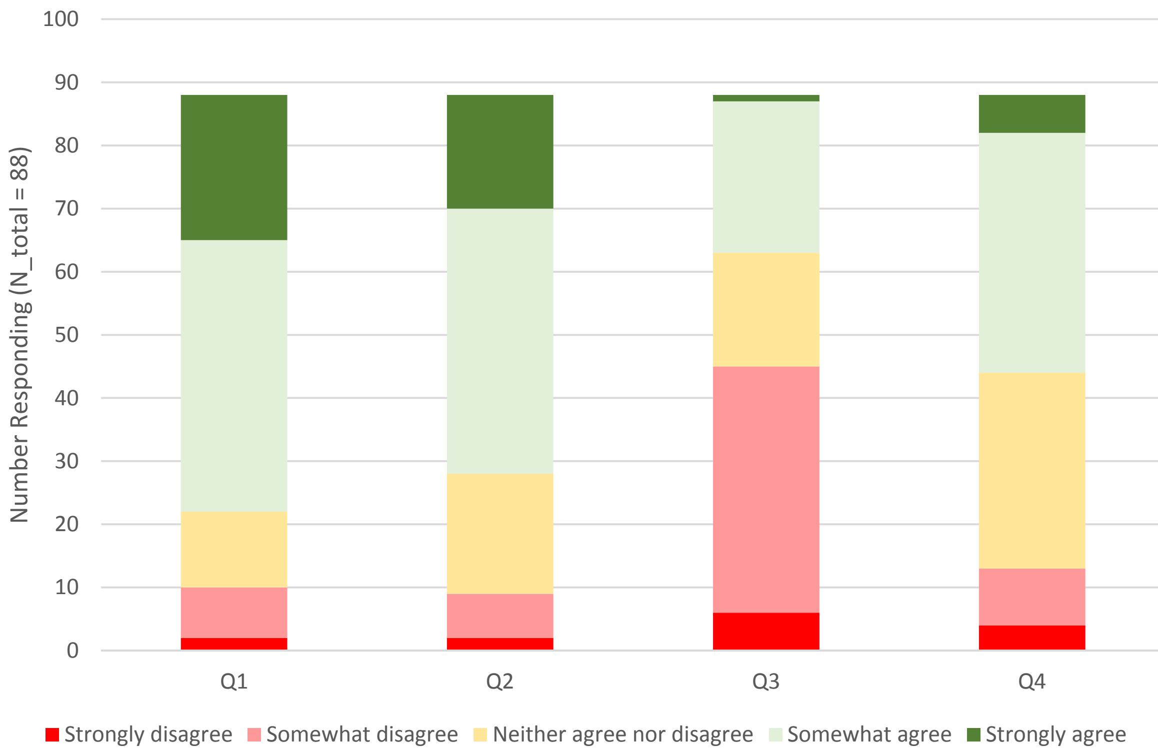

FIGURE 5: STUDENT SURVEY RESPONSES (N_{TOTAL} = 88)

Students were also asked whether or not they used the CSM to assist with their semester design project. Use of the CSM was not required, but the tool was made available for students to seek out if desired. Fifty-four students reported using the CSM, with 33 reporting not using the CSM and one abstaining from the question (N_{Total} = 88). This result was surprising to the instructors, as their perceptions were that the CSM was not widely used beyond the initial assigned activity. Those responding "yes" were asked a follow-on question as to whether or not they found the CSM helpful for identifying the evaluation metrics and constraints for their project. Of the 54 students who used the CSM for the project, 41 replied that the CSM was "Somewhat" or "Very Helpful," 10 replied that they were "Indifferent," three replied that the CSM was "Somewhat Unhelpful," and no one reported that it was "Very Unhelpful."

Discussion of Instructor Rating Consistency

The evaluation rubrics provided in Tables 3-5 proved useful in broadly determining which constraint sources the students performed best and worst on. In particular, students struggled in understanding the difference between customer safety (C-10) and societal safety (S-8). This could be in part due to not carefully considering the descriptions of each constraint source, or perhaps due to difficult or confusing wording in the instructions. It turned out that the instructors' ratings were most inconsistent for S-8 as well, indicating that this misconception between customer and societal safety may not have been based on experience. This result has highlighted an area where further development may be needed in both the CSM itself and/or the evaluation instructions.

Table 6 shows the rubric score ranges for each first-year student's responses for the Environmental-Technical (T-4) and Safety-Societal (S-8) attributes. For each metric, the range of the four instructor evaluations were tallied, then summed for each student. For example, when all instructor scores matched, the range was calculated as 0 (shown in green), demonstrating perfect agreement. On the other hand, instructor scores that included a "Low/Weak" and a "High/Strong" had a range of 2, indicating poor agreement (red). The Environmental-Technical evaluation ranges show a relatively high-level of agreement among the questions reviewed, while the Safety-Societal ranges show poor agreement.

TABLE 6: RANGE OF REVIEWER EVALUATIONS FOR FRESHMEN RESPONSES TO ATTRIBUTES T-4 AND S-8

Student Response ID	Reviewer Range (T-4)				Reviewer Range (S-8)			
	Depth	Relevance	Validity	Overall Score	Depth	Relevance	Validity	Overall Score
F-1	1	1	1	3	1	2	1	3
F-2	1	1	0	2	2	2	2	6
F-3	1	1	2	4	2	2	2	6
F-4	1	0	0	1	0	2	1	3
F-5	1	1	1	3	1	1	2	4
F-6	1	0	0	1	1	0	1	2
F-7	0	1	1	2	1	1	1	1
F-8	1	1	1	2	1	1	1	2
F-9	1	1	1	3	1	2	1	3
F-10	0	1	1	2	1	1	0	2
F-11	1	2	1	4	1	1	1	3
F-12	1	1	1	1	1	2	1	3
F-13	1	2	2	5	1	1	1	3
F-14	0	0	1	1	1	2	1	3
F-15	1	2	1	4	1	2	2	4
F-16	1	1	0	2	2	1	1	4
F-17	1	1	1	1	2	2	2	6
F-18	1	1	1	3	0	0	1	1
F-19	0	0	0	0	1	1	1	2
F-20	1	1	1	2	2	2	2	6
F-21	0	1	1	2	0	1	1	2
F-22	0	1	1	1	0	0	1	1
F-23	0	1	0	1	2	2	2	6
F-24	1	1	1	2	2	2	1	4
F-25	1	1	1	3	2	2	2	6
F-26	1	1	0	2	1	1	2	4
F-27	1	1	1	3	2	2	1	4
F-28	0	1	0	1	0	1	1	2
F-29	1	1	1	3	1	1	1	3
F-30	1	1	1	3				

Looking at the individual reviewer ranges for depth, relevance, and validity, the Degree of Relevance ratings varied the most across all constraint sources that were reviewed. The increased rating variance suggests that the instructors interpreted the attribute definitions and examples differently from one another. Again, evaluator scores are intended to assess a CSM user's understanding of each attribute and its impact on the design space. However, it is clear that a more common understanding of each attribute is necessary from the evaluators' various perspectives, a key issue that must be addressed to improve the overall reliability of the CSM.

It should be noted that the four instructors performing the evaluations did not discuss the CSM attributes or overall evaluation goals prior to performing the evaluations. The only resources available were the CSM itself and the provided evaluation instructions. Although this lack of preparation was not ideal for interrater reliability purposes, this type of approach likely replicates what is to be expected when the CSM is used in the field; that is, instructors cannot be expected to participate in extensive training sessions before applying the CSM tool. Thus, the inconsistencies found in this study give valuable insight on the aspects of the CSM that necessitate additional attention. Future improvements to the CSM will include discussions among the instructors to shore up some of the observed scoring inconsistencies.

Preliminary Comparison of User Groups and Future Work

As shown in Table 7, the average response scores (here employing a five-point Likert scale from 1 = "Definitely Not" to 5 = "Definitely") among the first-year, senior, and practitioner surveys varied little from group to group for several of the constraint sources. Average scores with ranges less than 0.3 points included topics related to ergonomics, affordability, environmental and competition; this is to say that in general, the three groups relatively agreed with one another regarding these constraint sources. There were, however, some constraint sources with relatively high average scores ranges (above 0.6 points) among the three groups; these included Safety-Customer (0.61), Safety-Societal (0.90), and Regulatory-Societal (1.06).

TABLE 7: AVERAGE SURVEY RESPONSE SCORES BY GROUP

Constraint Source	***Freshmen***	***Seniors***	***Practitioners***	***Range***
C-2 Aesthetics	3.26	3.05	2.75	0.51
C-4 Ergonomic	4.60	4.37	4.50	0.23
C-6 Learnability	4.37	4.11	3.92	0.46
C-10 Safety	3.48	3.47	4.08	0.61
S-1 Affordability	4.61	4.47	4.42	0.19
S-3 Environmental	2.47	2.37	2.50	0.13
S-7 Regulatory	3.35	3.47	4.25	0.90
S-8 Safety	2.67	2.11	3.17	1.06
B-1 Competition	3.70	3.84	3.67	0.18
B-6 Regulatory	3.83	3.42	3.58	0.41
B-9 Sustainability	2.32	2.63	2.25	0.38

While it is impossible to draw definitive conclusions from this preliminary data, particularly due to the small sample sizes and need for CSM refinement, some initial discussion points nonetheless arise. Most notably, it is worthwhile to point out the three high-variability constraint sources fall within the realm of liability and compliance – topics which are not often highly stressed in engineering college coursework – with the practitioners placing a greater degree of importance on these sources than the students. It could thus be argued that an improved understanding of external impacts from this type of oversight may better prepare students for professional careers. On the other hand, the students generally believed that the aesthetics and learnability (*i.e*., ease of use) of a potential product for the given scenario should be more highly prioritized than the practitioners, an unexpected outcome that will require additional investigation. Also worth noting is the variability of survey answers within each group. For each of the 15 questions, there was at least one first-year student who rated the constraint source as "Definitely Not" important and at least one who rated it as "Definitely" important. While perhaps not completely unexpected due to the larger number of first-year students ($N_F = 96$), this was also true for the 19 seniors on eight of the questions, and true for the 12 practitioners on four questions. For example, in response to the question, "Is it probable that the regular use of this type of product might have a potentially negative impact on the environment?" most of the practitioners selected "Probably Not" and "Maybe." Yet one practitioner selected "Definitely Not" while another selected "Definitely."

Although these converging results may allude to the conclusion that participants tended to agree more as their engineering experience increased, in fact there was an overall greater amount of variability among the practitioners' scores (the average standard deviation for each constraint source was 1.14 points) than the other two groups (both averaged a standard deviation of 1.05 points). These results call into question the idea that practicing engineers have relatively consistent views towards constraint sources. This divergence in answers among peers may be attributed to a number of possible causes, including (a) varying perspectives on each constraint source as it relates to one's own personal beliefs or experiences, (b) varying perspectives on the given scenario and how it relates to each constraint source, and (c) misinterpretation of the constraint source questions themselves. A more thorough qualitative analysis of the participants' justifications for their answers is thus warranted.

In conclusion, the Constraint-Source Model shows promise for eliciting more in-depth consideration of the numerous areas of constraints and the role these constraints can play in preliminary design thinking, as demonstrated by the generally positive freshmen survey results. This, in turn, has the potential to compel students to remain cognizant of the realistic limitations in engineering, better preparing them for the professional world. Students may also be more receptive to general education courses once they realize the impact that those topics may have on engineering design. Using the CSM compels students to view design from various perspectives, ideally leading not only to an improved comprehensive understanding of the problem, but also to an improved appreciation for the product-human interface and culturally-driven factors (*i.e.*, more empathetic); this in turn may strengthen their appreciation for diversity as well as their motivation for studying the humanities. Future research efforts include conducting additional analyses and iterations of the CSM to improve the model's evaluative consistency, to explore how the use of the CSM impacts later stages of the design process, and to investigate the student mindset relative to the importance of various constraint sources.

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