Proceedings of TMCE 2020, 11-15 May, 2020, Dublin, Ireland, edited by I. Horváth and G. Keenaghan

PERCEIVED IMPORTANCE OF ENGINEERING REQUIREMENTS BASED ON ORIGIN: AN EXPERIMENTAL STUDY

Chase Wentzky
Department of Mechanical Engineering
Clemson University
ecwentz@g.clemson.edu

Nick Spivey
Nicole Zero
Maria Vittoria Elena
Dr. Joshua D. Summers
Department of Mechanical Engineering
Clemson University
nwspive@g.clemson.edu, nzero@g.clemson.edu,
melena@g.clemson.edu, jsummer@clemson.edu

ABSTRACT

Requirements play a pivotal role within the engineering design process as they provide parameters and guidelines, as well as defining the success of a project. While there is significant research that explores how to elicit requirements, there is little experimental exploration of how engineers prioritize requirements based on the stakeholder sources for the requirements. Non-technical factors may affect the prioritization of the requirements. A user study was conducted with sixty-six third year mechanical engineering undergraduate students participating in the experiment. Each student was provided two design problems with a requirements document for each. For one of the requirement documents, participants were also provided information on the stakeholder owner of the requirement (sources). Although all of the requirement sources affected the weight given to requirements – typically in the positive direction – it is found that the source had a statistically significant influence on perceived criticality for only 25% of the requirement cases. To conclude, the sources did prove to affect the prioritization of the requirements. Future work will explore how the sources influence requirements based on different typologies, such constraints versus criteria, or requirements with and without numerical targets.

KEYWORDS

requirements, prioritization, user study, engineering design, design problem, organizations

1. INTRODUCTION

Requirements are used in engineering design to establish the desired outcome for a new product or system [1]–[5]. These requirements can be related to the function of the product itself or the means by which the product is created, such as the deadline for completion or the cost of producing the product [1], [6]. A requirements list is often developed as part of the early stages of the design process [1], [2]. The requirements list plays an important role in the development of the problem; thus, it is crucial that this list is well established so it can lead to a successful solution [7]. Part of the requirements list development involves ranking the importance of each requirement [8], [9]. It has been shown that requirements in a list can be ranked in terms of each individual requirement's technical importance and the cost of implementing that requirement [8], [10]. A requirements list is typically established by a variety of sources ranging from customers to members of the design or production team [11]. The requirements list drives the project development, highlighting the importance of defining these requirements in an optimal manner.

Requirements are often defined by a variety of stakeholders [12]. These stakeholders have differing opinions of the project, and sometimes, hold various weight in deciding which requirements are necessary to include. Previous research has observed how requirement sources can affect a solution [13], [14]. If a requirement is introduced by a member of the design team, it can be subject to change since the requirement was not set by the customer and may not be appropriate for a successful solution, despite initially being thought to be useful [15]. On the other hand, a requirement set by the customer is usually a "must-have" for the project and cannot be omitted [12]. It has been shown that having a diverse variety of requirement sources has a positive impact on a design [16]. Little research has been conducted, however, on how the source of a requirement affects a designer's perception of the importance of that requirement.

This paper focuses on the following research question: "How do designers perceive the criticality of a requirement based on the stakeholder source that provided the requirement?" A user study applied four test cases to two separate design problems to study this phenomenon. Through this analysis, insight is gained on how certain requirement sources are perceived by designers. The last of the four test cases did not contain a documented requirement list and was included in the study as part of a separate study. While the sketches are analyzed, the weight of the requirements themselves are also observed to determine if there is a relationship between the designers given weight of a requirement and if it is addressed in the solution. Coupled with the requirement source test cases, this research can contribute to mitigating any negative perceptions of a requirement source, especially if a crucial requirement is perceived as irrelevant or superfluous. This work may also build on *in-situ* evidence from cross-disciplinary industry projects [17]. Additionally, any non-technical factors influencing the perception of requirements can be observed based on the differences in the presentation of the requirement sources.

1.1. Requirement Classification

Not all requirements are the same type, thus, it is important to classify them into different categories [18], [19]. Requirements can be categorized, at a high level, by whether they are considered a criterion or a constraint [1]. Some requirements can also be assigned a target value. Further, requirements can be classified according to their source. Because requirements may be handled differently based on their structure, form, or source, these categories can be useful in developing user studies and analyzing design experiment data. Although this study focuses specifically on requirement origin as the independent variable, multiple ways of classifying a requirement exist and are briefly summarized in section 5.1 as areas of further exploration.

1.2. Sources

Requirement sources are the focus of this paper and are defined as the source from which a requirement is generated or provided. Previous literature defines the source of a requirement as the customers, users, observation of the market, or in-house domain experts of a design problem [20]. In this paper, the sources of a requirement are narrowed down from the high-level "in-house domain experts" group to the lower level groups of legal, manufacturing functions, the design team, project managers, or vice-presidents. This aligns with findings about requirements stakeholders from case studies on requirement cultures at various companies [21], [22]. The six stakeholders identified for this analysis are shown below in Table 1.

Source	Description
Legal	In charge of patents, regulations laid out by government, sustainability, and other regulatory agencies.
Manufacturing	Realizes the designs into mass produced products and ensures product quality.
Marketing	Responsible for gathering customer requirements. Decides market segmentation and product line.
Project Manager	Heads a team of product designers and reports to the top management on design progress.
Teammate	Belongs to the same design group or cross-functional engineering group with whom you collaborate.
Vice President	Heads all product and process proceedings and is responsible for the entire development process.

Table 1. The six requirement stakeholders listed in the experiment

Requirement sources have not previously been observed at such a level described in this paper. Thus, the goal of this inquiry is to determine if the internal source of a requirement can influence a designer's perception of the importance of a requirement. This sheds light on whether designers show a tendency to address technically important requirements in their solutions or tend to only address requirements that come from particular sources.

The client is a person or group that wants the creation of the product and they can either be external or internal to the company. The designer develops requirements that satisfy all sources. The user is the person or group of people who will use the product once it is created, and therefore has different requirements than the client and the designer, that must be satisfied. Categorizing and recording the source of the requirement can be useful in keeping track of changes, additions, and responsibilities [12].

A similar perspective on requirement sources includes all stakeholders that are affected by the characteristics of the design [23]. This list includes parties of internal stakeholders within the company, such as marketing, manufacturing, engineering, or production, as well as the end user that will be using the product and the client who will buy the product and then sell it to the end user. Governmental organizations, who typically provide legal and safety regulations, is another source of requirements that must be sustained for the product to be approved. The six sources developed for this analysis aimed to capture the breadth of requirement sources that practicing designers may encounter.

2. EXPERIMENTAL SET-UP

The experiment was administered to section of a required third year mechanical engineering course on design of machine elements. All the 66 participants were between 20-35 years old with more than 70% of the participants having completed some sort of internship or cooperative education experience. Less than 10% had worked in a full-time position in a technical field. While the participants had some project experience from their previous coursework or extracurricular activities, none of the participants had completed the required design methods course in the mechanical engineering curriculum.

Each participant received a packet with two fictional design problems. These problems presented participants with a simple design challenge that would allow participants enough time to read through a list of requirements and generate sketches, all within a 75-minute window. A list of twenty requirements was provided for each of the problems. The participants were asked to provide a "weight" to the requirement using an ordinal scale, describing the requirement's criticality. The weights given to the requirements with sources are then be compared to weights given to those same requirements, *without* listing the requirement source. The six sources were distributed in approximately equal proportions based on each particular test case and allowed for triangulation of the effects of their presence.

To ensure participants had ample time to thoroughly read through the problem statement and sources, weigh the requirements, and then generate sketches, a pilot study was conducted on an interdisciplinary group of graduate participants. During this pilot study, test subjects received one of the proposed problem statements to help establish how much time participants needed to weigh the requirements. The pilot revealed that participants who were required to weigh the requirements, and then sketch solutions, spent similar amounts of time as those participants who were asked to immediately sketch after reading the design prompt. It was also found from the pilot study that most of the designers stopped sketching after generating their second or third solution, which all occurred within a fifteen-minute period. For this reason, a time limit of fifteen minutes was given for each of the two problems.

2.1. Design Problems

The design problems used in this study are reused from previous design experiments – a practice which is not uncommon in the design research community [24]. Problem 1 was sourced from an experiment studying function representations [25] and Problem 2 came from a study on conceptual design [26]. The design problems used in this analysis are shown below in Table 2.

Problem 1: Burrito Folder [25]
A tool company called Outdoor Tailgating Co. is throwing a tailgating party at a football game for all of its employees. This year, they plan to provide burritos to the attendees during halftime and are expecting 200 people to attend. The task of manually making the burritos for this many people is very laborious; as such, the company would like to design an automated burrito making device. The device should: (1) prepare and fold burritos automatically, (2) complete a single burrito within 45 seconds of ingredient selection, (3) be able to select the ingredients attendees want on the burritos, (4) cost no more than $200, (5) also be designed to be easily manufactured.
Problem 2: Nail Remover [26], [27]
While in her home workshop, a carpenter occasionally needs to remove an unwanted nail from a given project. For this project, the carpenter needs to remove a nail without causing damage to her almost completed project. Normally, she might use the classic pry technique; however, the nail is in such a confined place that the pry will not work. You are a designer at Hobbyist Tools Inc. and have been tasked with designing a device to solve this problem. The device should: (1) not damage the material, (2) remove the nail, (3) cost less than $50, (4) be designed to be easily manufactured, and (5) not enlarge nail hole during removal.

Table 2. The two design problems given to each participant.

The two fictional design problems were chosen mainly based on their similarity, which was verified through the use of several metrics [28]. First, both problems are not technical in nature, meaning that they could both be understood by engineering novices. This style of problem was important to ensure that the undergraduate engineering participants could easily interpret each problem statement. Each problem was analyzed by its structure. As shown in Table 3, each problem contained just over 100 words, with Problem 2 having one more sentence than Problem 1. Similarly, each of the problems required seven lines of space when printed in size 12 font and contains a similar number of words per sentence. Lastly, five requirements were defined in each problem description, ensuring that the effects of being included in the problem statement would be similar in each case. While the reading grade level varied slightly for each of the two problems, the reading level did not exceed the academic experience of the participants, so both were deemed acceptable.

Problem 1: Burrito Folder					
Words	114	Words per sentence	28.5	Flesch-Ease	38.2
Sentences	4	Characters per word	4.7	Grade-Level	13.5
Lines	7	Given Requirements			5
Problem 2: Nail Remover					
Words	111	Words per sentence	22.2	Flesch Ease	62.3
Sentences	5	Characters per word	4.4	Grade Level	9.1
Lines	7	Given Requirements			5

Table 3. Problem statement metrics used in [28] describe the problem similarity for this experiment.

2.2. Test Cases

To test the effects of sources on how engineers perceived the importance of a particular requirement, three test cases were developed. The first test case (Case A) contained a list of requirements accompanied by a list of rationally linked sources. For example, "The device must cost less than $50" was given the source "Marketing" to describe a scenario when a product management group would provide a price target for a design. Case B contained the same list of requirements as those listed in Case A, but the source of each requirement was randomly assigned. In Case C, subjects would receive only the list of requirements for the problem, but had no sources listed. As mentioned previously, the fourth case (Case D) had no documented requirements process and was included as part of an analysis focusing on requirements and sketches. Each participant received a different test case for each of the problems, meaning that no student repeated the same test case for both the burrito folder problem and the nail remover problem. The layout of the possible test cases is shown below in Table 4.

Design Problem	**Problem Case**					
Burrito Folder	A – Rationally Linked	**N = 15**	B – Randomly Assigned	**N = 15**	C – No Sources Listed	**N = 18**
Nail Remover	A – Rationally Linked	**N = 16**	B – Randomly Assigned	**N = 16**	C – No Sources Listed	**N = 9**

Table 4. The possible test cases any given student may receive. Each student received a different case for either problem.

Arrangements of the test cases for each of the two problems were generated to organize the packets in such a way that every permutation of test case, in any order, would be covered in the user study. This was critical to determining the effect of the presence of requirement sources, as to control for the potentially confounding effects of test case or problem order. After each of the packets was generated, they received a unique identifier that aided in coding of the data using the source protocol.

2.3. Data Collection

The first page of the packet contained the packet's unique identifier and served as a cover sheet to ensure all of the participants started at the same time. On the next page, after reading the problem statement for the given problem, participants would then review a list of sources and their description (if given Case A or B), and would then turn to the third page, where they would be given a list of requirements in Cases A, B, and C. For Cases A and B, each requirement was also accompanied by one of the six sources. In Case C, the requirements were given with no source, and participants were then asked to weigh their perceived importance of each requirement from 1 to 6, and a sample of this is shown in Figure 1. The participants were not constrained to an integer response.

After the participants evaluated and weighted each requirement based on importance, they continued by sketching solutions to the presented problem. The participants were asked to explain each sketch as necessary for up to six solutions. The participants were asked to wait for the study administrator to present them with a second design problem. They would then repeat the process for a different test case. At the end of the packet, a short participant survey was also included that inquired about a participant's work

Proceedings of TMCE 2020, 11-15 May, 2020, Dublin, Ireland, edited by I. Horváth and G. Keenaghan
© Organizing Committee of TMCE 2020, ISBN ----------------------------

Please weight the requirements according to criticality from 1 to 6 (1 being the least important and 6 being the most important).

Requirement	Sources	Weight
The machine should be powered by battery and from a power socket.	Marketing	

Figure 1. Example of the requirements weighting activity with a listed source.

experience in an internship or co-op and exposure to design methods from previous coursework.

2.4. Experiment Execution

The full experiment was conducted in a classroom a setting, with each of the packets being handed out to participants in a randomized order. The experimental environment was familiar to all participants. Participants were asked to wait for the instructor to tell them to begin reading the first page of the packet, and to not discuss their design solutions within anyone else in the classroom during the test. Participants were then asked to begin and were given a five-minute warning before time was called. Participants who finished their designs before the first fifteen-minute period were asked to stop at the "STOP" page, to ensure every student had an equal amount of time to sketch as many design solutions as they felt necessary. After participants finished their design solutions for the second problem, and the fifteen-minute allotted time had passed, the packets were collected for analysis.

Packets from two participants were excluded from the data due to a failure to follow verbal instructions; the participants in these two discarded packets either left the column for requirement weight empty or placed all "sixes" in the weight column. While not constrained to responding in integers, all participants responded with weights of 1, 2, 3, 4, 5, or 6.

3. ANALYSIS & RESULTS

The first consideration for the analysis of the data was ensuring that the different test cases were not affected by the order in which participants received the two problems, or by the order of the given test cases. It was found that there was no statistically significant difference in means between participants who had the burrito problem first versus the nail remover problem as the first problem in their packet. Likewise, there was no significant difference in means between participants based on the order of the test cases. For example, a difference of means hypothesis test showed no significant difference in means between participants who received Case A first, then Case C second, versus participants who received Case C first, then Case A second. These tests were a vital part of ensuring that the comparison of the test cases would serve as a sufficient method of isolating the effects that sources had on a designer's perceived importance of a requirement.

3.1. Overall Source Effects

The analysis for this user study was conducted primarily through the mean weights given to requirements, and through statistical tests to determine if there was a difference in the perceived criticality of a requirement between the different test cases. The difference in mean weights when given each requirement source is shown in Table 5. The first was a comparison of Cases A, B, and C. Case A had requirements with rationally linked sources, Case B had randomly assigned sources with the requirements, and Case C had requirements without sources in the same order as Case A. It should be noted that Case B was added to randomize the test cases given to participants, by simply changing the order of the sources given in Case A.

Source	| Total Average Change |	Positive Effect Only	Negative Effect Only
Marketing	0.369	0.458	-0.167
Manufacturing	0.343	0.309	-0.364
Vice President	0.780	0.857	-0.497
Legal	0.502	0.522	-0.243
Project Manager	0.485	0.608	-0.312
Teammate	0.413	0.648	-0.272
ALL	0.482	0.589	-0.313

Table 5. The effects of listing requirement sources are shown for each of the six sources.

The comparison could then determine if there are any statistical differences between the responses of participants given sources versus a student that was not given sources. The goal for this study was to determine if the presence of sources matter (either purposefully or randomly assigned) when compared to requirements listed with no sources. The average change in requirement weight when given a source (in both the positive and negative direction) is shown below for each of the six sources in Table 5. The absolute value of the total average change due to the presence of a source is shown in the second column.

After comparing the data from Case A (requirements with rationally-linked sources) and Case B (requirements with randomly assigned sources) to the data from Case C (requirements with no sources), it initially appeared that the presence of sources next to each requirement did have some effect on the perceived importance given by the test subjects. In the burrito folder problem, the percent difference found between the cases with sources versus the case with no sources ranged from a 14.7% *decrease* in perceived importance, up to a 58.1% *increase* in perceived importance. The average change in perceived importance for the burrito folder problem was a 5.5% increase in weight over the requirements listed with no source. In the nail remover problem, the percent difference found between the cases with sources versus the case with no sources ranged from a 14.8% *decrease* in perceived importance, up to a 135.7% *increase* in perceived importance. The average change in perceived importance for the nail remover problem was a 7.5% increase in weight over the requirements listed with no source. As shown in Table 5, the absolute value of the average change in requirement weight when given a source was a modest 0.482 points – a 12.9% increase over the baseline weights with no source. This moderate aggregate effect of the sources meant that further statistical analysis needed to be conducted to discern how the specific sources affected requirement weights.

3.2. Statistical Testing

Although the presence of requirement sources did affect the mean weight given to the requirements for each of the six sources, whether or not the changes were significant was explored through statistical means. To better understand the specific instances in which the presence of a source affected the weight given to a requirement in a statistically significant way, a difference of means test was appropriate. However, due to the relatively small sample size of individual cases, and because the set of responses for any given requirement was typically not normally distributed, non-parametric tests were determined to be the most appropriate test for comparing the data. Participants were asked to weigh each requirement using an ordinal scale ranging from 1 (least important) to 6 (most important). As such, the Mann-Whitney U-test was used to determine the statistical significance of a change in the weights given to a requirement when a source was listed (Case A and Case B) versus when the requirement was on its own (Case C). Because the distribution of weights varied for any given requirement, this test was especially useful since it assumes no specific distribution, unlike the traditional t-test [29]. The twenty cases shown were evaluated at three different levels of significance, with the plurality of cases being significant at $\alpha = 0.05$. Sources for each of the statistically different requirements are shown in Table 6.

Source	Change in Perceived Importance When Listing Requirement Source			
Legal	0.64 *	1.33 ***	0.73 *	
	0.73 *	1.47 ***		
Manufacturing	-0.80 *			
Marketing	0.61 *	0.85 **		
Project Manager	1.67 ***			
Teammate	-0.67 **	1.02 ***	0.84 **	1.15 ***
Vice President	1.43 ***	0.78 *	1.83 ***	1.17 **
	0.81 *	1.08 ***	1.31 ***	

Mann-Whitney U-test shows significant at:
*** - $\alpha = 0.05$, ** - $\alpha = 0.10$, * - $\alpha = 0.15$

Table 6. The twenty instances where listing the requirement source led to a significant change (positive or negative) in the perceived importance of the requirement, at three levels of significance.

One immediate observation from the statistical analysis is that the sources causing the significant differences are rather varied. Although the source "Vice President" appears the most out of the six sources, there appear to be further underlying factors affecting a designer's perceived importance of a requirement that were not identified in this study. Through further exploration of identifying potential reasons for these source-specific changes, implications for requirements documentation and requirements writing could be found. These underlying factors will be discussed in the following section.

4. DISCUSSION

As stated previously, there appears to be potential underlying factors affecting requirement weights. Evidence from the frequency of sources, requirement topic, and participant survey given after the activity is linked to activity responses; using this information, the potential reasoning behind many of the significant changes is discussed.

4.1. Summary of Source Effects

As shown in Table 7, each of the possible sources for the requirements appeared between twelve and fourteen times, with a total of 80 “opportunities” for the requirement source to affect the weighting given by subjects. These frequency numbers serve as a summary of the information found in Table 6.

Source	#	Significant Increase	Significant Decrease	Freq. of Effect
Legal	14	5	0	36%
Manufacturing	13	0	1	8%
Marketing	13	2	0	15%
Teammate	14	3	1	29%
Vice President	14	7	0	50%
Project Manager	12	1	0	8%
Totals	80	18	2	**25%**

Table 7. A summary of the frequency of statistically significant effects from Table 6 is shown.

The presence of the requirement sources affected subject weighting at least once for every requirement source, with the most frequent effect being observed when “Vice President” was the source (N = 7) and least frequently when “Manufacturing” or “Project Manager” was listed as the source (N = 1). In total, out of the 80 possible opportunities for sources to affect how participants perceived a requirement importance, there were only twenty instances where a source made a statistical difference in how a participant ranked each requirement. This means that the presence of sources in requirements only significantly changed the way a student perceived them in 25% of cases – certainly not a majority of the time. Another observation is that the direction of the affect was overwhelmingly positive; in other words, when the inclusion of a requirement source affected the weights given to the requirement in a significant way, the affect was positive 90% of the time.

Another perspective for understanding the source effects was to view these statistically significant changes based on the requirement topic. Requirement topics were gathered for use in this analysis from the “requirements checklist” from [1]. As shown below in Table 8, the requirement topic for instances where a requirement source led to a significant change in weight are listed. In the third column, it is shown that the sources present appear rather sporadically in relation to the topic of each requirement. As the statistically significantly effects of the presence of sources only occurred in a quarter of the cases tested here, the below sample appears too small to statistically isolate requirement topic as an explanatory variable. However, this could serve as another perspective for analyzing the perceived importance of requirements, had the number of statistical differences been larger.

Requirement Topic	Frequency	Source(s) Present
Energy	4	Legal, Marketing, Vice President
Geometry	3	Legal, Project Manager, Teammate
Assembly	2	Legal, Teammate
Ergonomics	4	Legal, Marketing, Vice President
Operation	3	Legal, Teammate, Vice President
Costs	1	Manufacturing
Safety	3	Teammate, Vice President

Table 8. Frequency of statistically significant effects of requirement listed by topic from [1].

4.2. Qualitative Observations

The finding that the presence of a source led to a *positive* significant change in requirement weight was observed in all but two cases. In these cases of a negative significant change, the requirement sources were “Manufacturing” and “Teammate”. This is not entirely unexpected given that the sources “Teammate” and “Manufacturing” had relatively low changes in average perceived importance when listed by a requirement as shown in Table 5. As stated previously, “Vice President” had the most frequent significant effect on the weight given to requirements, affecting the weights half of the time it appeared in the lists. To make sense of these two extremes and provide possible explanations for these findings, evidence from the post-activity participant survey was considered.

In the survey, it was found that 73% of participants had some work experience in the form of an engineering internship or the cooperative education program, but only 9% of participants had any *full-time* experience in a technical field. This may help to explain the high frequency of roles like "Vice President" and "Legal" as statistically significant sources for requirement weight, alongside the rare frequency of "Project Manager" as a significant source. Since a majority the participants had work experience at relatively lower levels of their firms (as interns), stakeholders like "Vice President" and "Legal" may have been individuals with whom the participants rarely interacted. This elevated and aloof positioning may be one reason these sources carried an inordinate amount of weight in the perceived importance given to its requirements. Participants were not asked whether or not their roles took place in a manufacturing-specific organizational structure, which may also explain the relatively low weights given to requirements listed with "Project Manager" and "Manufacturing" as their source.

The source "Teammate" led to a significant change in the negative direction in one instance, and in total, had a moderate average effect on requirement rating. "Teammate", who was described as belonging to the "same design group or cross-functional engineering group" as the participants, was the "lowest" level of stakeholder described from an organizational perspective.

While this is one explanation for this relatively low weighting, another explanation may be that only a quarter of participants had taken their curriculum's engineering design course, a course that requires students to work on a collaborative design project. This lack of significant project experience could potentially be another reason for these lower requirement weights when "Teammate" was listed.

5. CONCLUSIONS & FUTURE WORK

With requirements playing a critical role on the success of a project, experiments like this one provide more context and clarity to the holistic understanding of requirements. The purpose of this study was to understand requirement prioritization based on sources for each requirement. The results from this user study shows that the sources positively affected the prioritization of the requirements, with statistically significant changes in requirement weighing in approximately 25% of cases. It is probable that this frequency of effect was influenced by the project experience and work experience level of the participants in this experiment. Understanding how other variables, like requirement structure, affect perceived importance, can be explored through the future work as described in the following section.

Several extensions to this research are identified as the next possible steps in developing a theoretical model to explain how sources influence perceived criticality of requirements. For example, a recent study that involved students as participants and practicing engineers has found that they behave similarly in requirements generation [30]. A confirmatory study in the future could compare the student participant performance against practicing engineers to help determine whether the experience in the workplace is a significant contributing factor in the high weighting for sources such as "Vice President" or "Legal". Alternatively, a study on confidence for solutions to address failure modes in a system found that there is a difference between non-domain generalists, domain generalists, and domain specialists [31]. Extending the requirements source study with participants from these populations could yield more insights into the degree to which experience can influence weighting the requirements.

Beyond studies that explore the differences between participant populations, studies could be explored with respect to different requirement classifications. Although the origin, or source, of the requirements was the variable studied in this analysis, future work could explore differences in the perceived importance of requirements due to other variables. If connections could be made between the structure of requirements, and those stakeholders presenting designers with the requirements, there exist multiple implications in requirements documentation and handling. Two of these variations in requirement structure are identified as potential areas for future work.

5.1. Constraints & Criteria

One variation in requirement structure that could be explored is how requirements can be classified as soft or hard. Hard requirements are a go/no-go situation in which the requirement must be met, also referred to as a "constraint" [12], [20], [23]. A soft requirement, or "criteria", is used as guidance and represents a desirable product trait, but not necessarily a mandatory one [12], [20], [23]. There are different views on classifying requirements as criteria or constraints. A first point of view is provided in [20]. To understand a client's problem, a set of objectives and constraints are needed. The "objectives" or "goals" are criteria, meaning they are desired characteristics of the design. The constraints are specific limitations that the design must satisfy to be suitable. The examples provided use the word "must" for requirement constraints and the word "should" for requirement criteria. A different perspective is instead provided by [23]. In this case it specifically states to avoid the words "must" and "should" and not classify the requirements into constraints and criteria but rather organize them into a hierarchy and subsequently establish their importance. This variation in the structure and semantics of a requirement could serve as another interesting avenue for user studies similar to this one.

5.2. Targets

Requirements can also be classified according to whether they include a target value or not. The inclusion of targets was a variation in requirement structure present in this study but was not a significant area of analysis. Targets are quantitative numerical values that the requirement should meet [12]. Setting a target adds details and specificity to the requirement [23]. Further, a target value is also useful when testing design prototypes. By meeting the target value, the requirement is satisfied. Even though most requirements should be quantified, some requirements do not have a target value but must still be described clearly [12]. Target values are observed in this work but were not included in the analysis as not introduce additional confounding factors. Future work may aim to determine the effects of target inclusion when requirements come from different sources.

ACKNOWLEDGEMENTS

The authors would like to thank the undergraduate students of Clemson University's "Fundamentals of Machine Design" course for their participation in this design activity. They would also like to thank the graduate students of Clemson University's "Research Methods in Collaborative Design" course for their help in serving as proctors and analyzing data for this study.

REFERENCES

[1] G. Pahl, W. Beitz, L. Blessing, J. Feldhusen, K.-H. H. Grote, and K. Wallace, *Engineering Design: A Systematic Approach*, 3rd ed., vol. 11. London: Springer-Verlag London Limited, 2013.

[2] D. G. Ullman, *The Mechanical Design Process*, 4th ed. New York, NY: McGraw-Hill, 2010.

[3] K. T. Ulrich and S. D. Eppinger, *Product Design and Developement*, First. McGraw-Hill, Inc, 1995.

[4] K. Otto and K. Wood, *Product Design Techniques in Reverse Engineering and New Product Development*. Upper Saddle River, NJ: Prentice Hall, 2001.

[5] C. Dym and P. Little, *Engineering Design: A Project-Based Introduction*. New York: John Wiley & Sons, Inc., 2000.

[6] S. J. Kapurch, "NASA Systems Engineering Handbook," *NASA Spec. Publ.*, 2007.

[7] D. Dvir, T. Raz, and A. J. Shenhar, "An empirical analysis of the relationship between project planning and project success," *Int. J. Proj. Manag.*, vol. 21, no. 2, pp. 89–95, 2003.

[8] G. S. Wasserman, "On how to prioritize design requirements during the QFD planning process," *IIE Trans.*, vol. 25, no. 3, pp. 59–65, 1993.

[9] Y. Akao, *QFD: Quality Function Deployment - Integrating Customer Requirements into Product Design*. Taylor & Francis, 2004.

[10] AFNOR, "NF X 50-151 Analyse de la Valeur, Analyse Fonctionnelle," Paris, France, 1991.

[11] A. Chakrabarti, S. Morgenstern, and H. Knaab, "Identification and application of requirements and their impact on the design process: a protocol study," *Res. Eng. Des.*, vol. 15, no. 1, pp. 22–39, Mar. 2004.

[12] J. K. Nisbett and R. G. Budynas, *Shigley's Mechanical Engineering Design*. 2002.

[13] X. Li and S. Ahmed-Kristensen, "Understand the design requirement in companies," in *Proceedings of the International Conference on Engineering Design, ICED*, 2015.

[14] B. W. Morkos, J. D. J. D. Summers, G. Palmer, J. D. J. D. Summers, G. Palmer, and J. D. J. D. Summers, "A Study of Designer Familiarity with Product and User During Requirement Elicitation," *Int. J. Comput. Aided Eng. Technol.*, vol. 5, no. 2–3, pp. 139–158, 2013.

[15] J. Lin, M. S. Fox, and T. Bilgic, "A requirement ontology for engineering design," *Concurr. Eng. Res. Appl.*, 1996.

[16] J. H. Tang and H. L. Yang, "User role and perception of requirements in a web-based community of practice," *Online Inf. Rev.*, 2005.

[17] E. Kamsties, K. Hörmann, and M. Schlich, "Requirements engineering in small and medium enterprises," *Requir. Eng.*, 1998.

[18] E. Worinkeng, S. Joshi, and J. D. Summers, "An experimental study: analyzing requirement type influence on novelty and variety of generated solutions," *Int. J. Des. Creat. Innov.*, vol. 3, no. 2, pp. 61–77, 2015.

[19] S. Joshi and J. D. Summers, *Requirements evolution: Understanding the type of changes in the requirement document of novice designers*, vol. 35. 2015.

[20] G. Auriol, C. Baron, and J. Y. Fourniols, "Teaching requirements skills within the context of a physical engineering project," in *Requirements Engineering Education and Training, 2008. REET'08.*, 2008, pp.

6–11.
[21] B. M. DelSpina, "Requirement Culture at a Large Scale Medical Device Developer : A Case Study," Clemson University, 2017.
[22] M. Elena, E. C. Wentzky, and J. D. Summers, "Requirements Culture: A Case Study on Product Development and Requirements Perspectives," in *ASME International Design Engineering Technical Conferences and Computers in Engineering Conference*, 2019, pp. IDETC2019-97017.
[23] E. Worinkeng and J. D. Summers, "Analyzing requirement type influence on concept quality and quantity during ideation: An experimental study," in *Proceedings of the ASME Design Engineering Technical Conference*, 2014, vol. 7.
[24] V. Kumar and G. Mocko, "Similarity of Engineering Design Problems to Enable Reuse in Design Research Experiments," in *Volume 7: 28th International Conference on Design Theory and Methodology*, 2016, p. V007T06A042.
[25] J. L. Richardson III, J. D. Summers, and G. M. Mocko, "Function Representations in Morphological Charts: An Experimental Study on Variety and Novelty on Means Generated," in *Interdisciplinary Design: Proceedings of the 21st CIRP Design Conference*, 2011, pp. 76–84.
[26] T. Hess and J. D. Summers, "Protocol Analysis: Studying Physical Manipulatives During Conceptual Design," in *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2014, p. V007T07A031-V007T07A031.
[27] T. A. Hess, "Investigation of Prototype Roles in Conceptual Design Using Case Study and Protocol Study Methods," Clemson University, 2012.
[28] A. Patel, M. V. Elena, and J. D. Summers, "A Systematic Approach to Evaluating Design Prompts in Supporting Experimental Design Research," in *ICED19: 22nd International Conference on Engineering Design*, 2019, p. no. 555.
[29] P. E. McKnight and J. Najab, "Mann-Whitney U-test," *Corsini Encycl. Psychol.*, p. 1, 2010.
[30] M. V. Elena and J. D. Summers, "Requirements Generation: Lecture Intervention Impact on Quantity," in *ASME International Design Engineering Technical Conferences and Computer in Engineering Conference*, 2019, pp. IDETC2019-97528.
[31] S. Thimmaiah, K. Phelan, and J. D. Summers, "An Experimental Study on the Influence That Failure Number, Specialization, and Controls Have on Confidence in Predicting System Failures," *J. Mech. Des.*, vol. 139, no. 1, p. 11102, 2017.