How Engineering Teams Select Design Concepts: A View Through the Lens of Creativity

Abstract

While concept selection is recognized as a crucial component of the engineering design process, little is known about how concepts are selected during this process or what factors affect the selection of creative concepts. To fill this void, content analysis was performed on student engineering design team discussions during a concept selection task. Our results indicate that student design teams typically focus on the technical feasibility of concepts during the selection process. However, teams that identified useful elements of ideas or continued to generate new ideas during this process had a tendency towards selecting creative ideas. These results add to our understanding of team-based decision-making during concept selection and highlight the need for encouraging creativity throughout the concept selection process.

Keywords: collaborative design; decision making; design education; engineering design; teamwork

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Creativity is regarded as an essential component of the design process and is required throughout the product development process in order to translate innovative ideas into successful products (Roy, 1993). As such, engineering design research has long sought to develop methods to enhance creative idea development in the early phases of design through the study of ideation tools (see for example (Altshuller, 1984; Eberle, 1996; Kulkarni, Dow, & Klemmer, 2012; Osborn, 1957). While the goal of these methods is to help designers generate a large quantity of effective solutions and explore a larger solution space (Shah, Vargas-Hernandez, & Smith, 2003), the creative ideas developed through these methods are often rapidly filtered out during the concept selection process (Rietzchel, Nijstad, & Stroebe, 2006) with few making it to commercialization. Since the evaluation process dictates which products to develop and which to abandon (Kijkuit & van der Ende, 2007), the concept selection process can be seen as the 'gate keeper' of creative ideas.

The process of selecting concepts that satisfy design goals has been regarded by researchers as one of the most difficult and elusive challenges of successful engineering design (Pugh, 1996) because of the impact this process has on the direction of the final design (Hambali, Supuan, Ismail, & Nukman, 2009; King & Sivaloganathan, 1999). Individuals and companies who select high quality and highly innovative concepts during this process increase their likelihood of product success and radical innovation, while those who select poor concepts have larger expenses including redesign costs and production postponement (Huang, Liu, Li, Xue, & Wang, 2013). These additional costs can greatly damage companies that are trying to survive in the fast-growing market that demands product innovations (Ayağ & Özdemir, 2009). In other words, for innovation to occur, creative ideas must be identified and selected through the concept selection process (Rietzchel, et al., 2006). However, individuals often select conventional or previously successful options during this process instead of novel ones (Ford & Gioia, 2000) due to their inadvertent bias against creative ideas (Rietzschel, Nijstad, & Stroebe, 2010). Specifically, researchers found that when left to their own devices, participants tended to select ideas based on feasibility to the detriment of creativity even though creativity did not necessarily lead to less feasible ideas (Rietzschel, et al., 2010). Therefore, even though creativity is emphasized in idea generation, due to people's deep-seeded desire to maintain a sense of certainty and preserve the familiar (Sorrentino & Roney, 2000), individuals may prematurely filter out novel ideas during the concept selection process regardless of merit in order to reduce risk. Thus, it is important that the field of engineering design shift its focus from identifying how to generate creative ideas, to identifying the factors that contribute to the filtering and promotion of creative ideas through the design process in order to increase the likelihood of innovation, which is crucial for long-term economic success (Ayağ & Özdemir, 2009).

Therefore, the goal of this research paper is to explore the team decision-making process during early-stage concept selection as well as the factors that impact the selection of creative ideas during this process. In order to accomplish this, an empirical study was conducted with 37 engineering students who performed a concept selection activity in design teams. The results from this study add to our understanding of the factors and themes that impact team decision-making and creative concept selection and outline new opportunities for increasing the effectiveness of concept selection methods and techniques in design education and research.

1 Background & Motivation

1.1 Design Considerations During Concept Selection

Concept selection is described as a convergent process that includes both the evaluation and selection of candidate ideas (Nikander, Liikkanen, & Laakso, 2014). Specifically, the first stage of the concept selection process occurs directly after concept generation when the design team is tasked with quickly evaluating dozens of concepts and selecting the ideas with most promise to move forward in the design process (Kudrowitz & Wallace, 2013). Concepts that were generated in previous stages need to be selected and synthesized into a final solution in order to address the design goal (Ulrich, Eppinger, & Goyal, 2011). Thus, initial concepts are evaluated for their strengths and weaknesses and for their ability to fulfill customer needs.

Various formalized methods utilize this same approach to help designers make decisions during this process (see Marsh, Slocum, and Otto (1993); (Pahl & Beitz, 1984; Pugh, 1991) for examples). These concept selection methods essentially assign attribute values to each generated concept and then attempt to compare and contrast the concepts in order to find an 'optimal' solution to the design problem. Technical feasibility is often the most emphasized consideration (Shah, et al., 2003), but other factors such as effectiveness (Ulrich, et al., 2011) and idea compatibility (Sivaloganathan & King, 1999) are also emphasized during this process. While the uniqueness or originality of the design is an important consideration during this process (Yang, 2009), these formalized design tools often neglect to consider creativity during the selection process (Genco, Holtta-Otto, & Seepersad, 2012). In fact, students are often taught to focus on technical rigor and conventional design solutions during engineering design education (Kazerounian & Foley, 2007), further reinforcing the focus on technical feasibility during this process.

These formal methods were developed to increase the effectiveness of the concept selection process. While has shown that these methods are increasingly being adopted by industry and have a positive impact on design practice (Telenko, Sosa, & Wood, 2014), many design teams still rely on informal methods of evaluating and selecting concepts (López-Mesa & Bylund, 2011; Maurer & Widmann, 2012; Salonen & Perttula, 2005). For example, concept review meetings are typical of engineering design practice where design concepts are discussed in a team setting and team consensus is reached by voting on which designs best address the design goal (Salonen & Perttula, 2005). Busby (2001) identified several important factors that influence this informal decision-making process through a series of unstructured interviews with professional designers. Namely, this study found that design robustness, novelty, production cost, and effectiveness all play key roles in informal concept selection practices. Individual level factors such as the designers' risk-taking attitudes has also been found to impact the selection of creative ideas (Toh & Miller, 2014) due to the uncertainty associated with novel ideas. Other researchers have shown that premature evaluation or convergence to a solution can negatively impact the idea generation process (Bearman, Ormerod, Ball, & Deptula, 2011). Still, other studies have shown that designers employ a variety of evaluation and problem-solving styles (Nikander, et al., 2014) that can result in differences in the creativity of final designs (Kruger & Cross, 2006). While these studies provide a foundation for investigating concept selection practices, the retrospective (interview) nature of the study, focus on professional designers, or lack of emphasis on team-based design discussions leaves to question what factors of the design are discussed during student team concept selection processes. Furthermore, these studies did not investigate the factors that encourage the selection of *creative* ideas. Researchers in the field of creativity (Baer, Oldham, Jacobsohn, & Hollingshead, 2007; Daly, Mosyjowski, & Seifert, 2014) widely accept the definition of creativity as the "production of novel, useful products" (Mumford, 2003, p. 110), or ideas that are both original and feasible. Therefore, the current study was developed in response to these research gaps.

1.2 Decision-Making in Design Teams

The study of the collective and collaborative decision-making process should also be investigated in any research that seeks to investigate informal decision-making practices. This is because design is considered an inherently collaborative process (Bucciarelli, 1988) that involves intricate communication patterns and roles that inadvertently impact the design process (Heath, 1993). Furthermore, design is being recognized and taught as a team process in engineering (Dym, 2003) in part because products developed by teams have been shown to be of higher quality than those produced solely by an individual (Gibbs, 1995) and in part because teams foster a wider range of knowledge and expertise which aid in the development of ideas (Dunne, 2000). In addition, teamwork has been shown to increase classroom performance (Hsiung, 2012) and encourage more creative analysis and design in engineering education (Stone, Moroney, & Wortham, 2006). In other words, team decision-making factors are as important, if not more important in determining the direction of collaborative design processes, and thus must be taken into account when studying naturally occurring design practices.

While research in student team communications during collaborative design discussions is limited, a number of studies have qualitatively explored the team decision-making process in design industry. In particular, many studies in design research analyze the design process as it occurs in practice in order to understand the "deeply collaborative, contingent, contextually-specific, and discursive" (Oak, 2010, p. 229) practice of design-decision making (Gero & Mc Neill, 1998; Yang & Epstein, 2005). For example, Christensen and Schunn (2008) analyzed the conversations of expert engineering designers during product development meetings and found that design prototypes tended to reduce the mental stimulation needed for innovative thinking. Other protocol studies such as those done by Dorst and Nigel (2001) show that some element of 'surprise' is necessary for the development of creative ideas by industrial designers. Researchers have also found that team-member seniority plays an important role in influencing team communication and decision-making. Another study by Stempfle and Badke-Schaub (2002) found that a lack of common understanding among team members occurred frequently, leading to extensive explanation and knowledge sharing sessions between team members. In addition, other researchers in this field have identified key patterns of communication such as negotiations among team members (Bond & Ricci, 1992) and established communication roles (Sonnenwald, 1996) as instrumental to team decision-making processes. Other team communication processes that have been shown to be important to collaborative design is the practice of building on team members' thoughts and ideas (Hargadon, 2003) and reacting in real-time to team activities (Buchenau & Fulton Suri, 2000).

These studies show that team decision-making processes are an important element of concept selection practices, and research that investigates the concept selection process in design must do so in the team context. However, the research lacks data on how these informal team decision-making processes affect the selection of creative ideas in the design process. This is problematic because we still lack knowledge of the factors that can influence design teams' perceptions and preferences for creativity, or how to best modify and implement concept selection methods that encourage creativity.

2 Methodology

The purpose of the current study was two-fold. First, we sought to explore the types of factors discussed when student design teams select or reject ideas during the concept selection process. Second, we sought to identify the types of factors discussed by student design teams who select more *creative* ideas during this process. To address these goals, a controlled study was conducted with engineering design students at a large northeastern university. During the study, participants were tasked with completing an idea generation and concept selection activity in design teams. The details of this study are provided in the following sections.

2.1 Participants

Thirty-seven engineering students (25 males, 12 females) participated in this study. Nineteen of the participants were recruited from a first-year introduction to engineering design course, while the remaining 18 participants were recruited from a third-year mechanical engineering design methodology course. Participants in each course were in 3 and 4-member design teams that were assigned by the instructors at the start of the course based on prior expertise and knowledge of engineering design (four 4-member teams, seven 3-member teams). This team formation strategy was used to balance the *a priori* advantage of the teams through questionnaires given at the start of the semester that asked about student proficiencies in 2D and 3D modeling, sketching and the engineering design process.

2.2 Procedure

At the start of the study, participants were given a brief introduction to the purpose and procedure of the study and were asked to complete an informed consent document. Participants then attended a design session where they were asked to develop a device to froth milk. One of the most elusive challenges of design research is selecting a task that is both representative of the design area and appropriate for the research questions being explored (Kremer, Schmidt, & Hernandez, 2011). The design task chosen in the current study was selected to represent a typical project in a cornerstone, or first year, engineering design course. In these courses, students are typically directed to redesign small, electro-mechanical consumer products that are equally familiar, or unfamiliar, to the student designers (Simpson & Thevenot, 2007; Simpson, Lewis, Stone, & Regli, 2007). This type of task is often selected because of the minimal engineering knowledge students have in these early courses. In order to ensure our participants were equally familiar with the product being explored, our design task went through pilot testing with first-year students prior to deployment. Specifically, relevant background information and the design problem for the current study were provided to participants in written form on paper, as seen in the Appendix. The design task involved developing concepts for a new product, and read as follows:

"Your task is to develop concepts for a new, innovative, product that can froth milk in a short amount of time. This product should be able to be used by the consumer with minimal instruction. Focus on developing ideas relating to both the form and function of the product."

In addition to the written instructions to generate innovative ideas, participants were also verbally reminded that the goal of the design task was to generate innovative early-phase design ideas instead of focusing on the feasibility or detailed design of the product. Once the design problem was read and understood, each participant was provided with individual sheets of papers and given 20 minutes to individually sketch as many concepts as possible for a novel milk frother. They were instructed to sketch only one idea per sheet of paper and write notes on each sketch such that an outsider would be able to understand the concepts upon isolated inspection, see Figure 1.Twenty minutes was selected for the ideation task because prior research has shown that most creative ideas emerge only after about 9 ideas have been generated (Kurdrowitz & Dippo, 2013) and creative idea generation tapers off at around 9 to 10 minutes of ideation time (Beaty & Silvia, 2012; Parnes, 1961).

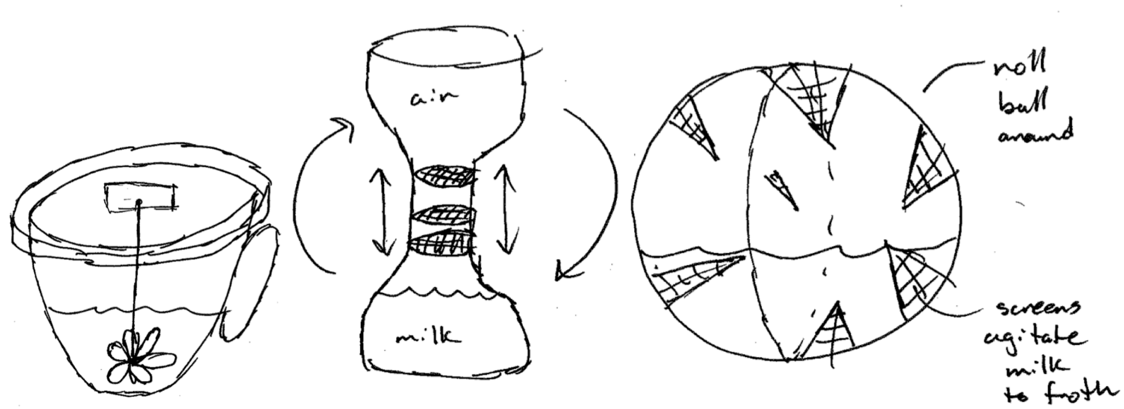

Figure 1: Example concepts sketched by participant T08LE.

After the brainstorming session, participants were asked to individually review and assess all of the concepts that had been generated by their team (including their own ideas) during the previous session. Once this was complete, the teams were given instructions for the team concept selection session, see Appendix for instruction sheet. Specifically, the teams were given the following task for this activity:

"…review and assess the concepts that you and your team have generated to address the design goal in a team setting. Once again, the goal of this design problem is to develop concepts for a *new, innovative,* product that can froth milk in a short amount of time."

Participants were asked to discuss each concept with their team members and once a team consensus was made, categorize the concepts as follows:

Consider: Concepts in this category are the concepts that will most likely satisfy the design goals; you want to prototype and test these ideas immediately. It may be the entire design that you want to develop, or only 1 or 2 specific elements of the design that you think are valuable for prototyping or testing.

Do Not Consider: Concepts in this category have little to no likelihood of satisfying the design goals and you find minimal value in these ideas. These designs will not be prototyped or tested in the later stages of design because there are no elements in these concepts that you would consider implementing in future designs.

These two categories were chosen to simulate the rapid filtering of ideas that occur in the concept selection process in industry (Rietzchel, et al., 2006). The design teams were asked to physically sort the generated concepts into these two categories and rank the ideas in the 'consider' category using post-it notes (1 being the best), see Figure 2. The team dialogue that took place during the discussions was audio-recorded using iPads placed at each team's workstation.

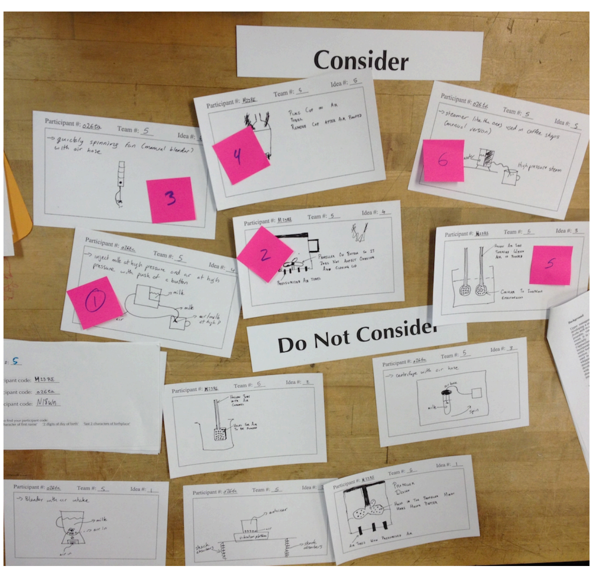

Figure 2: The sorting of team generated concepts into the 'Consider' category and 'Do Not Consider' category by Team 5.

2.3 Quantitative Data Metrics

Once the study was complete, two independent raters were recruited to assess the creativity of the ideas that were generated in the study using a 20-question Design Rating Survey (DRS) that had been developed in previous studies investigating the creativity of generated designs (Toh & Miller, 2014). The questions on the DRS were used to help the raters classify the features each design concept addressed, similar to the feature tree approach used in the previous studies (Toh & Miller, 2014). The raters achieved a Cohen's Kappa (inter-rater reliability) of 0.88, and any disagreements were settled in a conference between the two raters *after* all ratings were completed as was done in previous studies investigating creativity (Chrysikou & Weisberg, 2005). The results from these concept evaluations were used to calculate the following metrics:

Idea Novelty: This metric was developed to capture the amount of novelty of each generated idea in this study. Since creativity is widely accepted as the "production of novel, useful products" (Mumford, 2003, p. 110), novelty was used as a proxy for creativity in this study. Novelty refers to the "measure of how unusual or unexpected an idea is compared to other ideas" (Shah, et al., 2003, p. 117) and is one of the most relevant concepts in the study of creativity in an engineering context. This is not only because novelty is often used synonymously with creativity (Torrance, 1964, 1964), but also because it captures the fundamental spirit of engineering- to create something new. Indeed, researchers have acknowledged the importance of generating 'wild ideas' and withholding judgments about feasibility during early stage ideation (Kelley & Littman, 2001) in order to encourage ideas that are new, unexpected (Sarkar & Chakrabarti, 2011), and valuable (Weisberg, 1993). Thus, the novelty metric was calculated for each generated design using the feature tree approach developed by Shah, et al. (2003) and described in Toh and Miller (2014).

Propensity Towards Creative Concept Selection, P_c: This metric was developed by the authors to quantify each team's tendency towards selecting (or filtering) creative concepts during the concept selection process. When developing this metric, the following items were considered:

1. Teams should receive a high score for selecting a large number of creative ideas from their idea set.
2. Teams should receive a low score for not selecting creative ideas if they are present in the idea set.
3. Teams must not be penalized for the lack of highly novel ideas within their idea set as long as they select the most novel ideas in their set.

Once these guidelines were established, the metric was developed as follows: The average novelty of the selected concepts was divided by the average novelty of all ideas generated by the team. This metric is shown in detail in Equation 5.

$$P_c = \frac{average\ novelty\ of\ selected\ concepts}{average\ novelty\ of\ generated\ concepts} = \frac{\sum_{j=1}^{k}(D_j \times C_j)}{k} \times \frac{l}{\sum_{j=1}^{l} D_j} \qquad (5)$$

Where P_c is the team's propensity for creativity during concept selection, k is the number of ideas selected by the team, l is the total number of ideas generated by the team, D_j is the novelty score of the j^{th} idea, and $C_j = 1$ if the idea is selected and 0 if the idea is not selected.

In essence, P_c measures the proportion of novel idea selection out of the total novelty of the ideas that were developed by the design team. This metric can achieve a value greater than 1 if the average novelty of the selected ideas is higher than the average novelty of all the generated ideas, indicating a propensity for creative concept selection. P_c can also be less than 1, indicating an aversion for creative concept selection. A score of 1 indicates that the team chose a set of ideas that, on average, had the same novelty as the ideas that they generated, indicating no propensity or aversion towards creative concepts during the selection process. In order to classify teams based on their level of creative concept selection, teams that scored above the mean score in the current study ($P_c = 1.01$) were considered to have high P_c, whereas teams that scored below the mean were considered to have low P_c.

2.4 Qualitative Data Coding Procedure

In all, participants generated 251 ideas and selected 91 ideas during concept selection. This resulted in 265 minutes of audio dialogue that was transcribed and coded by two independent coders. "The transcripts of the team dialogue was then analyzed using principles of inductive content analysis (Mayring, 2004) in NVivo v.10 (QSR, 2012). The limited and fragmented prior knowledge about student team discussion topics during concept selection makes this method useful for analysis in this study (Lauri & Kyngas, 2005). Following this approach, the team dialogue was analyzed sentence-by-sentence through open coding, and initial categories of discussion topics were created. The two coders identified instances of discussions (defined as a block of dialogue between the team members on a particular topic) and classified these discussions into either ‘consider’ or ‘do not consider’ based on team decisions. Next, general themes regarding discussion topics were identified, and the number of instances of discussion topics, as well as their word counts were computed. Similar categories were then grouped together to reduce the number of categories (Burnard, 1991), in order to sufficiently describe the types of topics student teams discussed during concept selection. The development of these themes and their sub-categories were directed by the content of the team discussions as well as prior research that provide a foundation for the types of factors that influence the decision making process in engineering design (e.g., feasibility, robustness, novelty, production cost, effectiveness) (Busby, 2001; Nikander, Liikkanen, & Laakso, 2014). While other methods of analyzing design team communication such as Linkography (Goldschmidt, 2014; Kan & Gero, 2008) and Latent Semantic Approach (Dong, 2005; Dong, Hill, & Agogino, 126; Fu, Cagan, & Kotovsky, 2010) have been developed and applied in the field of engineering design Content Analysis was chosen for this study due to its ability to process large volumes of data with relative ease in a systematic manner (Crowley & Delfico, 1996).” The two coders achieved an inter-rater agreement of 79.5% for this initial analysis, and any disagreements were settled in a conference between the two raters *after* all ratings were completed.

4.3 Results and Discussion

In order to address our research goals, the data from the generated concepts and the coding of the team discussions was analyzed. The following sections present the detailed results of our analyses in the order of our research questions.

3.1 Discussion Topics During Team Concept Selection

Our first research goal sought to investigate the factors that impact team's decision-making process during the concept selection process. Specifically, we analyzed the team discussion transcripts to uncover general themes behind the selection or rejection of concepts to move on for further development. In all, 6 main discussion topics and 16 sub-topics were identified; see Figure 3 for the list of these topics and frequency of occurrence. It should be noted that not all discussions led to the selection or rejection of a concept. For example, a participant in Team 4 commented on the technical feasibility of a concept, but the discussion did not lead to the selection or rejection of the idea; "I don't know if this will work, but I like the idea." Therefore, the frequency counts for discussions that led to selection or rejection does not necessarily equal the total frequency of occurrence of each discussion topic. The following sections present detailed descriptions and examples of these discussion topics as they occurred during team concept selection discussions.

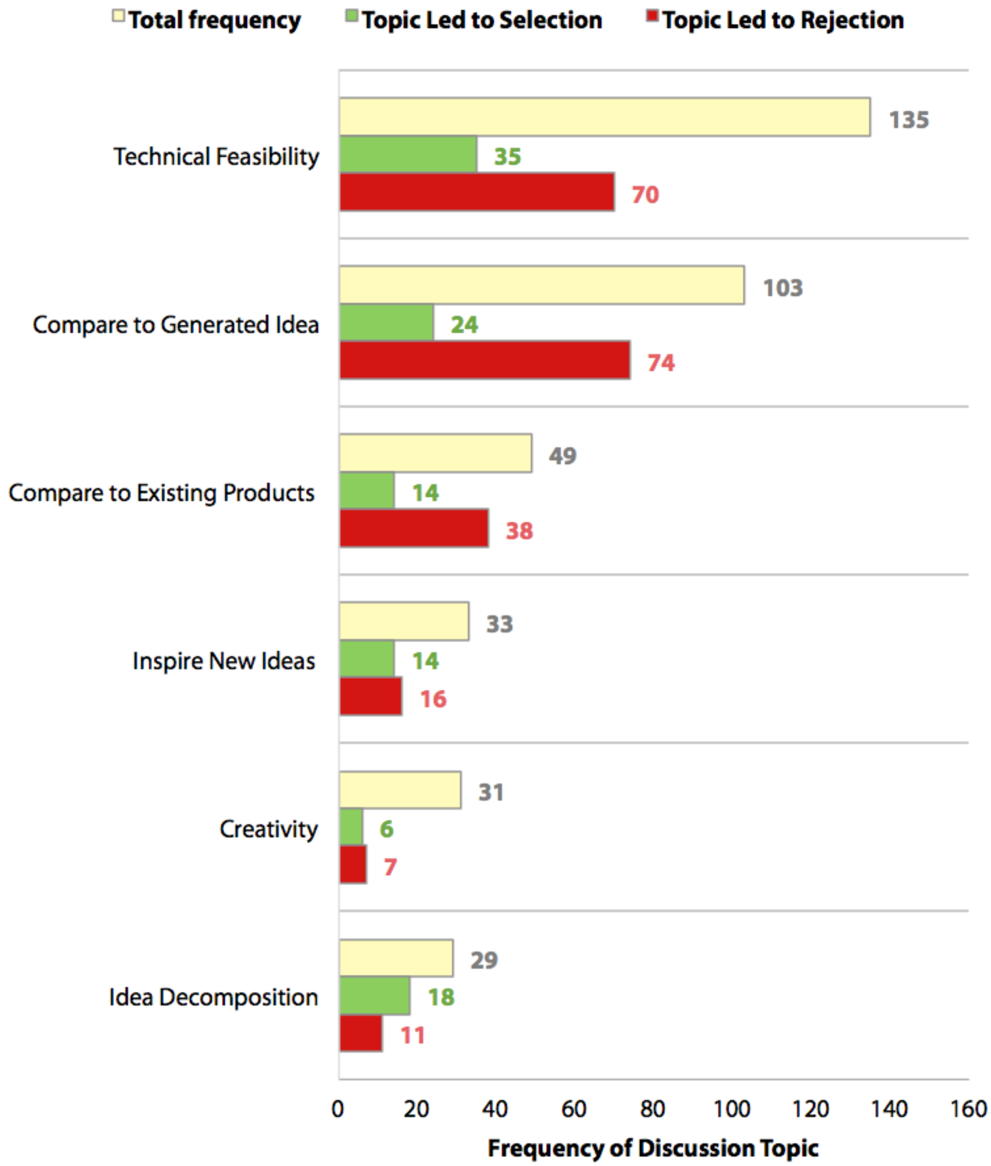

Figure 3: Discussion topics, their total frequency of occurrence, and the number of times the topic led to the selection or rejection of a concept. Not all discussions led to the selection or rejection of a concept, resulting in frequency counts for selection or rejection that do not equal the total frequency of the topic.

3.1.1 Technical Feasibility

The discussion topic that was most frequently discussed by the design teams during concept selection was the technical feasibility of the ideas (f = 128), which included discussions about the ease of execution and effectiveness of a concept in satisfying the design goal. Five sub-topics in this area were also identified including:

ability to satisfy design goal (f = 82), *maintenance* (f = 35), *efficiency* (f = 13), *economics* (f = 12), and the *manufacturability* of the design (f = 2). As can be seen by the frequency of these topics, the majority of the discussions on technical feasibility involved the ideas' *ability to satisfy the design goal*.

Specifically, the teams often discussed different methods of frothing milk and the ability of each method to forth milk quickly and easily. In other words, teams were focused on whether the generated ideas "worked or not". For example, a participant in Team 4 commented on a generated design: "That one, I'm not sure how it will work. Like you need another component inside of it to spin and stuff." *Maintenance,* or amount of effort and upkeep required of a design, was also frequently discussed in this topic. For example, participants in Team 1 discussed the maintainability of a generated concept (see Figure 4) in detail and eventually decided to reject the concept because it "would be hard to clean". This focus on the maintenance of the product is consistent with engineering design education that emphasizes meeting customer needs throughout the design process (Ulrich, et al., 2011).

Figure 4: Example concept generated by a participant in Team 1 that was considered difficult to maintain and ultimately rejected by the team.

Overall, these findings demonstrate that student design teams focus a great deal of their discussions during the concept selection process on the technical feasibility of the generated designs. This finding is supported by prior work that has shown that practical considerations are a vital component of the design decision-making because designs that are impractical or impossible to develop ultimately have no value in the design process (Shah, et al., 2003). These discussions are also in-line with current educational practices in engineering design that heavily emphasize design functionality, often relying on well-proven solutions to engineering problems (Kazerounian & Foley, 2007).

3.1.2 Idea Comparison

The second most discussed topic during team concept selection involved the comparison of generated ideas with one another (f = 125). These discussions allowed teams to benchmark concepts with previously generated designs and eliminate any redundant ideas. This is important because individuals tend to generate ideas in a 'train of thought' manner where successive ideas often share many semantic similarities (Nijstad, 2002). During these discussions, teams either talked about the *Similarity* (f = 81) or their *Preference* (f = 22) for one generated concept over another. Teams often used these discussions to compare the merits and disadvantages of each idea in order to make decisions regarding each generated idea. For example, a participant in Team 2 voiced their preference for one idea over another: "…I like this one better, because when you are using this one you have to have a lot of milk in there..."

This process of comparing and contrasting information is common in engineering design since formal concept selection techniques utilize this approach to help designers make effective decisions (Saaty, 2008). At a more fundamental level, cognitive psychologists have long since recognized the importance of using prior relevant information in order to make judgments (Blumenthal, 1977). In fact, researchers have shown that the cognitive processes involved in analyzing similarities and making decisions are closely linked (Medin, Goldstone, & Markman, 1995), further highlighting the important role that comparisons play in decision-making.

3.1.3 Similar to Existing Products

The third most frequent discussion topic involved comparisons to other similar products that already exist in the market (f = 49). Discussions about existing products served several important roles in facilitating team discussions and were broken down into 2 sub-topics: *Explanation* (f = 40) and *Proof of Concept* (f = 9). Design teams often used examples to clarify details and provide further explanation for the generated ideas. Since the design sketches produced by participants were preliminary in nature and occasionally lacked sufficient detail to be clearly understood by the rest of the design team, participants also used existing products as analogies during the team discussion. For example, a participant in Team 1 used an existing product to explain the working principle of their generated concept: “Like two egg beaters. If you’ve ever had an egg beater, it’s just like that.” Other discussions involved using existing products as *proof of concepts* or justification of the feasibility of generated ideas. That is, participants would argue that since an existing product uses a specific operating principle, generated ideas that share the same operating principle should be equally successful.

These findings show that the use of existing examples is pervasive during team discussions and serves a crucial role in facilitating effective team decision-making. This is supported by prior research that regards the use of existing products as important for benchmarking and is a staple of engineering instruction (Ulrich, et al., 2011). In addition, researchers have provided evidence for the benefits of using existing examples during the creative process (Herring, et al., 2009) and have shown that existing solutions to problems encourage analogical thinking and help designers draw insightful similarities between situations (Chan, et al., 2011). Other research has shown that ideas that are innovative and distinct from existing products add value to the design process (Yang, 2009). Thus, these studies show that existing examples serve an important role in stimulating thinking and facilitating decision-making especially during concept selection.

3.1.4 Inspire New Ideas

The fourth topic discussed by participants in this study involved discussions that inspired new ideas. During these discussions, team members collaboratively proposed new ideas or elements of an idea amidst the concept selection activity. Since students were explicitly instructed to stop generating ideas and start concept selection, students were not expected to perform idea generation during concept selection. Rather, this discussion topic involved hypothetical conversations among team members regarding changes to the generated ideas that would better address the design goal. These discussions were often motivated by the need to modify an idea in a manner that would make the idea favorable to all team members. This discussion topic was further broken down in 2 sub-topics: *Element Modification* (f = 24) and *Combining Ideas* (f = 9). The first sub-topic involved a simple addition or modification of one or multiple elements of a generated design. This occurred mostly because teams favored all but one element of a generated design and concluded that changing that element would make the design successful. For example, a participant in Team 1 suggested a design modification: “Well you know all of yours had wiring going up to the lid but instead you could have it be battery powered.” Design teams also engaged in discussions that led to the combination of two or more ideas that were generated by the team.

This process of generating new ideas from existing ideas through the recombination, modification, and adaptation of elements has been recognized as a staple of collaborative design practice (Gerber, 2007). In fact, this process has been argued to be crucial to the generation of truly creative ideas that would not have existed if not for the combination of several designers’ ideas (Hargadon, 2003). However, this practice of building on ideas may not be fully encouraged in engineering education since idea generation and concept selection are thought of as disjointed processes that occur one after another, as opposed to in conjunction.

3.1.5 Creativity

The fifth discussion topic, creativity, involved discussions about the uniqueness and originality of a generated design. Discussions about the creativity of the design were broken down into either positive elements of the ideas’ *Creativeness* (f = 23) or the ideas *Lack of Creativity* (f = 83). Design teams most often engaged in discussions regarding the creative aspects of the generated designs, and used these discussions to break ties between two competing ideas and narrow down the final pool of selected ideas. For example, a participant in Team 2 commented on a generated idea: "This would be a really unique idea and actually applicable." On other occasions, creative ideas were rejected by teams during the discussions (26% of the time). For example, a participant in Team 10 commented on a generated idea: "It's fun but not practical. I feel like the milk will get churned or something." The sub-topic *'Idea is Not Creative'* involved discussions regarding the *lack of* creativity in generated designs. Unlike the previous sub-topic that involved discussions either favoring or rejecting creative ideas, this sub-topic typically focused on the disadvantages of unoriginal or redundant ideas. In other words, while design teams may be generally ambivalent about the importance of creativity during concept selection, they unanimously considered ideas that were unoriginal as not useful in addressing the design goal.

These results show that the creativity was rarely discussed in team concept selection discussions despite the fact that participants were encouraged to generate creative ideas during this study. In fact, the topic of creativity was the *second least* discussed topic during team discussions, highlighting the fact that creativity was neglected during the concept selection process. This neglect for creativity is said to occur due to people's bias against creativity, fueled by the uncertainty and risk associated with novel concepts (Rietzschel, et al., 2010). This paradox of creativity in the engineering design process is especially concerning in an educational context since recent research has shown that engineering courses lack instruction and assessment frameworks that encourage creativity in the classroom (Daly, et al., 2014) often resulting in upperclassmen who are less creative than first-year students (Genco, et al., 2012).

3.1.6 Idea Decomposition

The final, and least frequently discussed topic refers to instances when the team decomposes a concept into its sub-elements and considers only one aspect of a design. This discussion topic was divided into 2 sub-topics: *Focus on Elements* (f = 20), and *Disregard Elements* (f = 9). Discussions where team members only focus on a single element of a generated concept involve detailed discussions about an aspect of the design that was considered useful. During discussions of the second sub-topic, design teams chose to consider an aspect of the design at the expense of other aspects. That is, design teams selected concepts that only contained a single element worth developing and simply ignored other elements that were not favored by the team. For example, a participant in Team 5 suggested: "Do we want to consider just for the idea of having a pouring mechanism?"

The pattern of decomposing concepts into its sub-elements and extracting a single element has been shown to be crucial to effective design thinking and reasoning (Rowe, 1987). Thus, more focus should be placed on developing instructional strategies that emphasize idea decomposition in order to encourage in-depth discussions and idea flow in a team setting (Ryan, 2005).

3.2 The Impact of Propensity of Creative Concept Selection on the Frequency of Discussion Topics

Once the discussion topics were identified, the relationship between the team propensity for creative concept selection and the frequency and word count of the discussion topics was investigated. Before testing our hypothesis, a preliminary analysis was conducted in order to determine the effects of the confounding factor of education level on team propensity for creative concept selection. However, a one-way ANOVA revealed that student level had no effect on the teams' propensity for creative concept selection score ($F = 2.10$, $p > 0.18$). A first multivariate linear regression analysis was conducted with the dependent variables being frequency at which each of the 6 discussion topics occurred during each team's discussion, and the independent variable being team propensity for creative concept selection. The results revealed that when taken together, the frequency of occurrence of the 6 discussion topics was significantly impacted by team propensity for creative concept selection, Wilk's $\lambda = 0.05$, $F = 13.96$, $p > 0.01$. Specifically, significant positive relationships were found between the frequencies of the 'Inspire New Ideas', and 'Idea Decomposition' discussion topics and P_c, see Table 1 and Figure 5.

Table 1: Summary of the first multivariate regression analysis with discussion topic frequencies as the dependent variables. Bolded rows indicate significant results.

(Discussion Topics) Dependent Variables	**Frequency of Occurrence**	**R^2**	**Sig.**
Technical Feasibility	135	0.04	0.57
Compare to Another Generated Idea	103	0.00	0.94
Compare to Existing Products	49	0.21	0.16
Inspire New Ideas	**33**	**0.67**	**0.00**
Creativity	31	0.01	0.83
Idea Decomposition	**29**	**0.49**	**0.02**

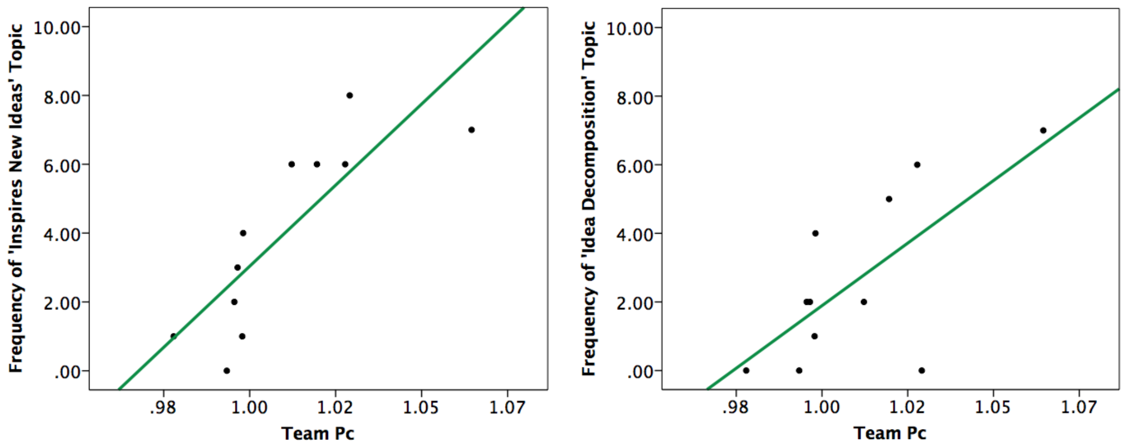

Figure 5: Team Pc scores and the frequency of the 'Inspires New Ideas' (left) and 'Idea Decomposition' (right) discussion topics.

A second multivariate regression analysis was conducted with the dependent variable being the word count of each of the 6 discussion topics, and the independent variable being team propensity for creative concept selection. The results revealed that when taking together, the word count of the 6 discussion topics was significantly impacted by team propensity for creative concept selection, Wilk's $\lambda = 0.06$, $F = 10.95$, $p > 0.02$. Specifically, significant positive relationships were found between the word count of the 'Compare to Existing Products' and 'Idea Decomposition' discussion topics and P_c, see Table 2 and Figure 6. It is also interesting to note that while creativity was the second least frequently discussed topic, participants spent the least amount of time on this topic in terms according to the word count frequencies.

Table 2: Summary of the second multivariate regression analysis with discussion topic word counts as the dependent variables. Bolded rows indicate significant results.

(Discussion Topics) Dependent Variables	Word Count	R^2	Sig.
Technical Feasibility	3642	0.05	0.51
Compare to Another Generated Idea	2636	0.07	0.44
Compare to Existing Products	**1862**	**0.36**	**0.05**
Inspire New Ideas	1209	0.34	0.06
Creativity	359	0.24	0.12
Idea Decomposition	**842**	**0.60**	**0.01**

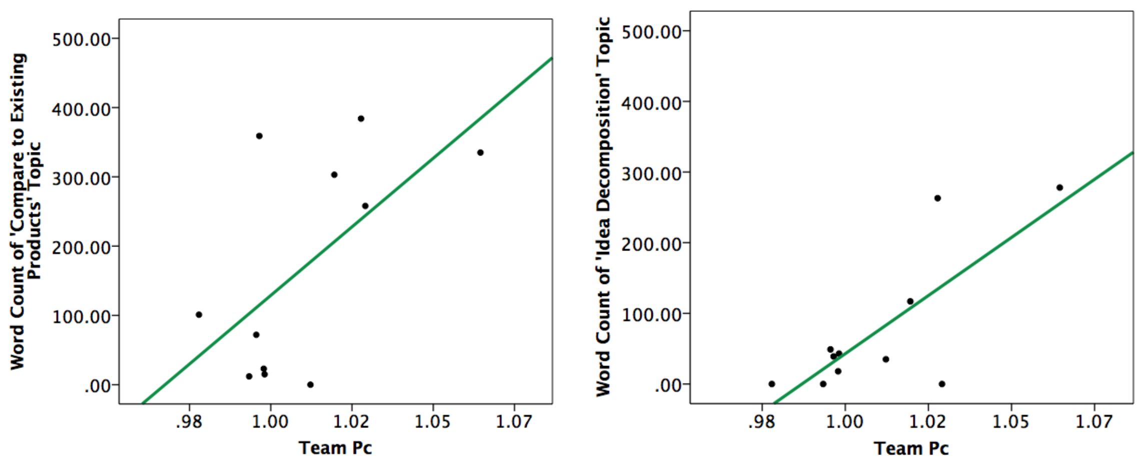

Figure 6: Team Pc scores and the word count of the 'Compare to Existing Products' (left) and 'Idea Decomposition' (right) discussion topics.

These results indicate that teams who selected more creative ideas tended to engage in more frequent discussions that *Inspired New Ideas,* see Figure 5. This finding supports the notion that the co-evolution of the problem and solution space is the "engine of creativity in collaborative design" (Wiltschnig, Christensen, & Ball, 2013, p. 515). It also adds to our understanding of the factors that contribute to creative concept selection in engineering design. Specifically, student design teams who spontaneously modify or combine generated ideas 'on the fly' during the concept selection process were more successful in selecting creative ideas during this process. This is despite the fact that students are generally taught to generate ideas *prior* to selecting ideas during formal design training. This result is supported by prior research that has shown that improvising and building on generated ideas is crucial for creativity in design practice (Gerber, 2007). This result identifies that encouraging students to not just select concepts, but to evolve their designs during the process can help increase design creativity in the classroom and provide students with further insights into industrial design practices. In addition, it shows that students should be encouraged to really consider the individual aspects of 'crazy' ideas in order to identify components that may be useful for further development.

Our study also found that student design teams that engaged in more frequent and elaborate discussions regarding *Idea Decomposition* were also found to select more creative ideas during concept selection, see Figures 5 and 6. This result indicates that teams who focused their discussions on single elements of a generated idea and dialogued about the disadvantages and merits of the idea within their teams eventually selected more creative ideas. In addition, these teams also frequently extracted a single favorable element of a generated design to be considered for further development, instead of considering each idea as a complete design that had to be considered at face value. This practice of extracting a single design element and engaging in discussion regarding that element is supported by prior design research on creative idea generation that encourages designers to draw on existing ideas and react in real-time to team generated ideas (Buchenau & Fulton Suri, 2000). The fact that student design teams engaged in this creative idea generation method *during* concept selection further highlights the fact that many of the skills and techniques employed during ideation can be implemented during concept selection in order to increase creativity.

Lastly, although there were no significant results for the frequency of occurrence of the 'Compare to Existing Products' discussion topic, the word count of this discussion topic was significantly affected by the teams' propensity for creative concept selection, see Figure 6. This result indicates that teams who dialogued more about comparison to existing products tended to select more creative ideas during concept selection. These teams used existing products as analogies of their generated ideas in order to have detailed discussions about the generated ideas, often benchmarking their ideas against other existing products (Ulrich, Eppinger, & Goyal, 2011). Although these teams did not necessarily compare their generated ideas to existing products more *frequently,* the higher word count of these discussions indicate that students were engaging in more lengthy and detailed discussions and using existing examples to inspire creative thinking through analogical thinking (Chan, et al., 2011), improving the creativity of the selected designs.

3.3 Impetus for Engineering Design Education and Research

The main goal of this research was to examine the concept selection process in student engineering design teams and identify the factors that impact the selection of creative concepts during this process. The detailed qualitative and quantitative analysis of team-based discussions by engineering design students revealed the following results:

1. Student design teams most frequently discussed the technical feasibility of generated ideas and often compared generated ideas with one another to make decisions during concept selection
2. Creativity was mostly neglected during team discussions despite it being emphasized in the earlier stages of the design process, and

3. Teams that selected more creative ideas tended to compare designs to other existing concepts, were inspired to modify designs during team discussions, and identified useful elements of concepts.

These results have several important implications for engineering design education and research. First, these results show that engineering design students are highly focused on technical feasibility during the concept selection process, as has been emphasized in the engineering curriculum (Kazerounian & Foley, 2007). Students in our study often engaged in detailed discussions with team members regarding the relative value and feasibility of generated concepts, citing engineering principles learned from courses and applying key knowledge structures important to rigorous engineering design. However, our findings also highlight the lack of focus on creativity during the concept selection process. While creativity is heavily emphasized in the earlier stages of the design process (Rietzchel, et al., 2006) and in engineering education (Litzinger, et al., 2011; Richards, 1998; Stouffer, et al., 2004; Sullivan, et al., 2001), the results from this study provide empirical evidence for the neglect of creativity during the concept selection process.

While it is important that students learn to recognize and select viable options during the design process, creativity is an important consideration that can increase the quality of design outcomes (Yang, 2009) and ultimately help encourage the design of engineering solutions that provide the most value to society. Therefore, it is clear that a re-framing and re-structuring of concept selection practice and instruction in engineering education is necessary if creative ideas are to pass through the concept selection process and ultimately add value to the design process (Rietzchel, et al., 2006). While our study highlights the neglect of creativity during the selection process, future research should be geared at investigating the impact of modifications in educational practices on both the selection of candidate ideas and the final design idea implemented in order to better understand the impact of educational structure on concept selection.

In addition to highlighting the neglect of creativity during the concept selection process, the results of this study also established an empirical link between the selection of creative concepts and the frequency of discussion topics. Specifically, our results indicate that teams who continue to act on inspiration and generate ideas during the concept selection stage of the design process tend to select more creative ideas. This finding provides evidence for supporting a more streamlined and coherent conceptual design process in engineering design education that truly allows for the co-evolution of problem and solution space (Wiltschnig, et al., 2013). This coupled approach to concept generation and selection cannot only increase creativity but can also improve the flexibility and effectiveness of the design process. Thus, design instruction and techniques that encourage designers to be inspired through idea generation and selection should be developed and implemented in order to improve the effectiveness of the design process and help encourage creativity.

4 Limitations and Future Work

While the current study highlighted the neglect of creative ideas during concept selection and identified factors that lead to creative concept selection, there are several important limitations that should be noted. Most important is that this study was developed primarily to explore engineering student's concept selection process in teams in situ through the lens of creativity. Future work should focus on studying design teams in industry to compare the results found in this study with design practice. Similarly, larger sample sizes and the investigation of other team-level and individual attributes may reveal a link between creative concept selection and discussions regarding creativity where one was not found in this study. Another important point to note is the fact that the current study focused on a single design task, and only considered the novelty of the generated ideas. While this study provides knowledge of how student designers select novel concepts for a specific design project, future studies that explore the novelty and feasibility of ideas generated in other design problems throughout the conceptual design process will help validate the results of this study. In addition, while this study investigated the team conversation in terms of frequency of occurrence and word count of discussion topics, future work that examines more detailed aspects of team discussions, such as the amount of time devoted to a discussion topic or the number of participants in a discussion can provide more insights into the team decision-making process in concept selection. Finally, while the current study showed a link between creative concept selection and the frequencies of these discussion topics, it is not clear if the increased discussion of these topics lead to creative concept selection, or simply if teams with more propensity for creative concept selection naturally engage in more discussions surrounding these topics. Further experimental investigations on this topic will reveal more information regarding the direction of this relationship.

5 Conclusions

The main goal of this study was to investigate engineering student concept selection processes through the lens of creativity in order to identify the factors that contribute to creative concept selection. To meet this goal, quantitative and qualitative analysis of data acquired from a controlled experiment with student design teams was conducted. Overall, the results of this study show that student design teams focused primarily on the technical feasibility of designs during team concept selection discussions, as is heavily emphasized in engineering education. However, this study also revealed that student teams rarely considered creativity during team discussions, highlighting the neglect of creativity during this process. Lastly, our results indicate that creative concept selection is related to higher frequencies of discussions on the decomposition of generated ideas and discussions that inspire the generation of new ideas, and higher word counts of discussions about existing products during concept selection. Our results are used to provide directions for future research and provide evidence for the need to develop instructional strategies that encourage creativity throughout the design process, particularly during concept selection. However, future work is needed to explore the impact of educational interventions or strategies to successfully promote creativity during this process.

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8 Appendix

Individual Brainstorming Instructions

Upper management has put your team in charge of developing a concept for a *new innovative product that froths milk in a short amount of time*. Frothed milk is a pourable, virtually liquid foam that tastes rich and sweet. It is an ingredient in many coffee beverages, especially espresso-based coffee drinks (Lattes, Cappuccinos, Mochas). Frothed milk is made by incorporating very small air bubbles throughout the entire body of the milk through some form of vigorous motion. As such, devices that froth milk can also be used in a number of other applications, such as for whipping cream, blending drinks, emulsifying salad dressing, and many others. This design your team develops should be able to be used by the consumer with minimal instruction. It will be up to the board of directors to determine if your project will be carried on into production.

Once again, the goal is to *develop concepts for a new,* ***innovative*** *product that can froth milk in a short amount of time. This product should be able to be used by the consumer with minimal instruction.*

Sketch your ideas in the space provided in the idea generation sheets. As the goal of this design task is not to produce a final solution to the design problem but to brainstorm ideas that could lead to a new solution, feel free to explore the solution space and focus on both the form and function of the design in order to develop innovative concepts. In other words, generate as many ideas as possible- do not focus on the feasibility or detail of your ideas. You may include words or phrases that help clarify your sketch so that your concept can be understood easily by anyone.

For clarity, please use the provided pen to generate your concepts (ie: do not use pencil). Your participant number is included on each of the provided idea generation sheets. Generate one idea per sheet and label the idea number at the top of the sheet.

Team Concept Selection Instructions

During this activity, you will once again review and assess the concepts that you and your team have generated to address the design goal in a team setting. Once again, the goal of this design problem is *to develop concepts for a new, innovative, product that can froth milk in a short amount of time.* Your task is to assess all of the generated concepts for the extent to which they address the design goal effectively **<u>in your design teams</u>**, using the following instructions:

1. Collect **all concepts that your team has generated** and shuffle them in random order. As a team, discuss which concepts should be 'Considered' and classified as 'Do Not Consider'. Categorize all the concepts your team has developed by placing them on the table with the corresponding category labels. For your reference, the category definitions have once again been provided below:

   Consider: Concepts in this category are the concepts that will most likely satisfy the design goals, Your team wants to prototype and test these ideas immediately. It may be the entire design that your team wants to develop, or only 1 or 2 specific elements of the design that you think are valuable for prototyping or testing.

   Do Not Consider: Concepts in this category have little to no likelihood of satisfying the design goals and your team finds minimal value in these ideas. These designs will not be prototyped or tested in the later stages of design because there are no elements in these concepts that your team would consider implementing in future designs.

2. After all concepts have been categorized, **rank all concepts in the 'Consider'** category only. As a team, come to a consensus on the rankings of the concepts. Place the Post-it notes on the concepts to rank them, with 1 being the best concept, 2 being second best, and so on.

3.