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A STUDY OF GALLERY METHOD TO INCREASE IDEA QUALITY IN CONCEPTUAL DESIGN

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A STUDY OF GALLERY METHOD TO INCREASE IDEA QUALITY IN CONCEPTUAL DESIGN

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ABSTRACT

The objective of this research is to evaluate whether gallery method increases idea quality in conceptual design for engineering design problems. The gallery method is a group ideation process which allows individuals to first generate ideas individually, followed by pooling of ideas to conduct group ideation. Design engineers are often encouraged to work in groups to generate concepts and solutions for design problems. However, past research argues that individual ideation results in higher quality design concepts compared to the group ideation methods. The limitations of group ideation such as free riding, production blocking, evaluation apprehension, and goal incongruity are identified to limit its effectiveness. However, group ideation is still popular in industry settings despite the identified limitations. There is a contrast between the past research findings and actual industrial practice of group ideation. This research identifies an opportunity to evaluate the combination of the merits of individual and group ideation through the gallery method for increasing idea quality in conceptual design.

The effect of gallery method is compared with individual ideation through two design studies to determine the best suited ideation method for increasing idea quality. In Design Study I the average quality of design concepts generated by the two ideation methods are compared. A Design Study II was conducted to replicate the results from Design Study I under new set of test parameters. This study also evaluated the effect of structured and non-structured gallery method to increase concept quality. In both the studies, the participants were asked to develop and sketch design concepts for engineering problems. The results from the studies indicated that the average quality of concepts generated by gallery method is higher than individual ideation for engineering design problems. However, there is a possibility that the limitations of group interaction and dynamics can compromise the effect of gallery method in increasing idea quality. Past research suggests the use of facilitator(s) during an idea generation process to reduce the limitations of group dynamics, increase the productivity and efficiency of groups. In this research, a preliminary investigation of facilitated gallery method was conducted through a workshop with three engineering design teams working on an industry sponsored project. A survey on the facilitated hybrid ideation workshop was conducted after the teams developed the conceptual designs for the project. The qualitative analysis of the data indicates that the presence of an external facilitator enhanced the performance and increased productivity of the teams.

DEDICATION

For Siddharth Nair, without your encouragement, support, kindness and unconditional love I could not have done this.

"Do not let your fire go out, spark by irreplaceable spark in the hopeless swamps of the not-quite, the not-yet, and the not-at-all. Do not let the hero in your soul perish in lonely frustration for the life you deserved and have never been able to reach. Check your road and the nature of your battle. The world you desired can be won. It exists, it is real, it is possible, it is yours."

Ayn Rand , *Atlas Shrugged*

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ACKNOWLEDGMENTS

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Chapter One
INTRODUCTION

The objective of this research is to evaluate whether the gallery method increases idea quality in conceptual design for engineering design problems. In light of addressing the objective, the following areas of literature are reviewed:

1. Discussion of concept generation techniques
2. Discussion on the findings from cognitive science studies comparing individual ideation and group ideation
3. Discussion on group ideation techniques, limitations and its practice

Several research opportunities are formulated on completing the literature review.

1.1 Motivation

Concept generation is an integral part of engineering design process [1-3]. It is generally accepted that the process of concept generation in a systematic design process begins after procurement of a design problem statement and is followed by these steps:

1. *Identification of customer requirements* – identifying customer demands and needs,
2. *Task clarification-* collect information about product requirements and classification of these requirements to constraints and criteria
3. *Formulation of requirements list* – develop an information document or checklist of all requirements [1, 2, 3].

During concept generation, designers seek design concept(s) to solve engineering problems. It is essential to understand that a systematic design process is iterative in nature. Designers begin with generating a range of concepts thus expanding the design space to increase the probability of discovering principle solution(s). A principle solution is defined as concept(s) that fulfills all requirements as well as most of the wishes and can be realized within the constraints of the budget [1].

Many concept generation tools and methods exist to aid in the concept generation process [1-7]. Designers either generate concepts individually or in group comprising of three or more members. Engineering design problems are complex in nature with one or more interacting components, involves continuous decision making and requires elaborate expertise to solve them. In industrial settings, engineers are often put together in groups or teams to leverage their abilities and skill set for solving complex engineering design problems. However, past research suggests that group ideation is relatively ineffective for concept generation and is described in detail in Section 1.3. The productivity and efficiency of a design team to meet its objectives is affected by members' interaction while working towards goal attainment. The process of concept generation using groups is identified with limitations and is described in Section 1.4. This research identifies the need to effectively combine the merits of both individual and group ideation to increase the probability of design teams to generate high quality concept(s). The gallery method is a group ideation technique that first allows individual ideation followed by group ideation (described in Section 1.5). The research identifies gallery method as the solution to effectively combine merits of individual and group ideation and assist design teams to generate high quality concepts and solutions for design problems. The aim of our research is to evaluate the effect of the combination of individual and group ideation through gallery method to allow individual members and the group as a whole to participate without any inhibitions towards developing high quality concepts. It is expected that the contribution from both individual and group ideation will increase the probability of design teams to explore and expand design space for high quality concepts.

Overall Research Objective: *To evaluate whether gallery method increases idea quality in conceptual design for engineering design problems*

1.2 Concept Generation Techniques

In engineering design, designers have to explore and expand design space thoroughly to generate ideas to meet the customer requirements. With an increasing competition amongst companies to deliver innovative, creative and high quality products to the customers under tight time constraints, designers are forced to develop innovative, creative and high quality ideas [7]. There are several idea generation techniques available to assist designers for generating ideas [1,9]. The process of generating ideas individually in isolation using an idea generation technique without any direct communication with others is called individual ideation [7-9]. Individual ideation can be conducted in the presence of indirect communication. In this research, direct communication is defined a process of communicating information in an explicit manner. The key features of direct communication include discussions and confrontations for achieving clarity [12, 13]. An indirect communication is defined as a communication process that leaves the conscious with a feeling of being communicated and a strong urge for further clarification [12, 13].

The key features of indirect communication comprises of communicating very little information through codes, transmitting information through non-assertiveness and in a non-argumentative manner [12]. The process where designers generate ideas in a group comprising of three or more members using an idea generation technique is called group ideation [4, 7, 8, 10–16]. Designers can generate ideas individually or in groups. Table 1.1 lists the fifteen most popular idea generation techniques used in engineering design to generate ideas individually or in groups during conceptual design process.

Table 1.1: List of most popular idea generation techniques used in engineering design for individual and group ideation

Idea Generation Technique	Individual Ideation	Group Ideation
Brainsketching with explanation of ideas [16], [19]		✓
Brainsketching without explanation of ideas [19]		✓
Brainwriting [12, 17]		✓
Checklists [3, 17]	✓	✓
C-sketch/ 6-3-5 [19]	✓	✓
Delphi Method [20]		✓
Fishbone [3, 17]	✓	✓
Functional Decomposition [1, 3, 4]	✓	✓
Gallery Method [1, 15]		✓
Mind Map [3, 17]	✓	✓
Morphological analysis [1, 3, 4, 17]	✓	✓

Idea Generation Technique	**Individual Ideation**	**Group Ideation**
Nominal Group Technique [20]		✓
Osborn's Brainstorming [15, 18, 19, 20]		✓
Synectics [1, 3, 17]	✓	✓
TRIZ [3, 17]	✓	✓

Table 1.1 summarizes several commonly accepted idea generation techniques that can be used only for group ideation such as Brainsketching with/ without explanation of ideas, Brainwriting, Delphi Method, Gallery Method, Nominal Group Technique and Osborn's Brainstorming. There are techniques that can be used for either group ideation or individual ideation Checklists, C-sketch/ 6-3-5, Fishbone, Functional Decomposition, Mind Map, Morphological analysis, Synectics and TRIZ. This research evaluates the effectiveness of gallery method during idea generation process. In this research, effectiveness of an idea generation process is defined as its ability to assist a group to generate high average quality ideas for a design problem.

1.3 Discussion on the Findings from Cognitive Science Studies Comparing Individual Ideation and Group Ideation

There have been several past studies focused on the effectiveness of group ideation in idea generation process. The group approach is widely used in organizations and despite its widespread usage hundreds of experimental studies from cognitive science have criticized group ideation [21, 22]. A study suggests that subjects brainstorming in small groups produce fewer ideas than the subjects generating ideas individually [10]. Another study conducted to find the effect of group participation on brainstorming concluded that individuals produced more ideas than groups; the quality of ideas generated by individuals was also higher than the quality of ideas generated by groups [14]. Another study concludes that group participation inhibits creative thinking [26]. A study of experimental comparisons of groups and individuals by Hill [27], provides mixed results on the effectiveness of individual ideation and group ideation on four dimensions: task, process, individual differences and methodology. This study suggests that superiority of groups over individuals at certain tasks is due to (a) pooling of ideas by the members of the group followed by correction of each other's errors and (b) the ability to use different strategies for concept generation more often than individuals. The group's size increased the probability of containing at least one member who could solve the design problem. On account of process loss (the aggregation of information, error checking or decision making and division of labor), groups did not always incorporate the best of their potential to the concept generation process [24, 25]. However, there is a contrast between the results of cognitive science literature and anecdotal evidence on the practice of group ideation in real organizations [25]. Another study argues that cognitive theories are derived from controlled experiments that use simple tasks whose suitability for complex engineering design problems has never been investigated [29]. Cognitive science provides models and theories which are derived from simple tasks or problems, whereas engineering design studies are representative of real world engineering problems [30]. Hill [27] suggests that a number of imaginative problems have been used in cognitive science experiments. The use of imaginative problems in cognitive science studies can be seen in the studies conducted by Dunnette et al.,[14] and Taylor et al., [23]. Decades of research (see

Table 1.2) analyzing the effectiveness of group ideation techniques to produce high quality ideas has resulted in misguided conclusions regarding their usability [28].

Table 1.2: Summary of results from cognitive science studies comparing group ideation and individual ideation

Reference	Conclusions
[26]	Group ideation inhibits idea generation potential of individuals in groups.
[14]	Individual ideation produced more number of ideas with greater quality than group ideation.
[31]	Individual ideation is more effective than group ideation to produce increased quality and quantity of ideas
[32]	Group ideation inhibits creative thinking. Individual ideation is more productive than group efforts
[27]	Group ideation is inferior to individual ideation. Performance of an exceptional individual performing individual ideation can be superior to a group consisting of low ability members.
[22]	Productivity of the participants in individual ideation is greater than group ideation. Production blocking significantly reduced the productivity of group ideation.
[30, 31]	Group brainstorming produces less number of ideas and relatively low quality ideas as compared to individual brainstorming.
[10]	Groups following brainstorming produced less number of ideas than participants following individual ideation.
[35]	Variance of idea quality is greater in individual ideation whereas mean quality of ideas is greater in group ideation.

1.4 Discussion on Group Ideation Techniques, Limitations and its Practice

Brainstorming is one of the most popular group ideation techniques used in concept generation. Osborn defined brainstorming as an idea generation technique where a group of open minded people from different spheres of life bring up, without prejudice, as many ideas as possible and thus trigger off new ideas in the minds of the other participants of the group [1]. From the time of its origin, brainstorming provided companies with an easy way to structure their group interactions, and became the most widely used creativity technique in the world; it is still popular in advertising offices and design firms, classrooms and boardrooms [24]. While idea generation can be an individual activity performed in isolation, it often requires expertise of multidisciplinary specialists [11]. Many engineering problems are complex and large that no one person has all the experience, insights or resources to solve the problem alone; in such cases specialists from multidisciplinary background must make a group effort to address the problem [36]. Smith [8] identifies brainstorming and brainwriting as two important group ideation techniques. In brainstorming, the members of a group generate ideas, evaluate ideas collectively, and stimulate additional ideas in other members of the group. In brainwriting, the members of a group share ideas non-verbally to reduce distractions and inhibitions. Another study suggests that brainstorming is the most common group ideation technique used in industries to generate creative ideas [5] Many firms have created 'idea factories' where teams generate ideas as a group to facilitate the generation of innovative and creative ideas [11]. Satzinger and colleagues [37] suggest that ideas generated by members of a group can be used by others to stimulate their own thinking to produce new ideas. However, several studies have identified factors that affect the effectiveness of group ideation techniques [4, 7, 15, 22, 24, 30–32]. The three most common limitations that are identified are free riding, evaluation apprehension and production blocking. These limitations are explained as follows:

- Free riding is encountered when members give up on the group to achieve objectives; individual efforts are not combined with efforts of others [21, 25]. This can result due to lack of motivation, accountability and effort to work collectively as a group.
- The productivity of a group can be reduced by the fear of critical evaluation from other members, thus inhibiting the performance of the individuals [22, 25]. This is called evaluation apprehension.
- Production blocking is observed when one person in a group speaks while others wait to speak, or when one member of a group is more dominant in expressing ideas than the rest of the members of the group [22, 37]. This results in lower satisfaction and reduced performance of the group members.

Amongst the various group ideation techniques, research suggests that the techniques using sketches for communication of design concepts are more effective than the ones that only use textual representation [5, 14, 33, 34]. A research on idea generation techniques, suggests that the 6-3-5 and brainsketching without discussion can cause misinterpretation of ideas for the members of a group due to the absence of communication or annotation of sketches [12, 15]. The lack of discussion on generated ideas can inhibit the members to interpret them and further development of the ideas. The idea generation techniques such as Delphi method [20] where individuals of a group never meet face-to face for making group decisions, has limitation due to the absence of verbal clarification or feedback on the ideas generated [43]. On the contrary, Delbecq [20] argues that nominal group technique (individuals in a group silently develop ideas followed by presentation of ideas to the group without discussion) are effective when members of group are physically present for idea generation and for problems that require immediate attention. The Delphi method is considered to be effective for generating ideas when members of a group cannot be physically summoned face-to-face to generate ideas or for problems that do not require immediate solution [20]. It is beyond the focus of this research to study the effect of idea generation techniques where members of a group do not meet face-to-face for generating ideas. This research focuses on group ideation techniques where a reliable and quick communication channel is available between different members of a group to generate ideas.

Research Opportunity 1: The findings from the cognitive science research on the effectiveness of individual ideation may not be applicable to the concept generation in engineering design. The features of both individual ideation and group ideation can be combined to leverage benefits of both in an idea generation process. The effect of group ideation to increase idea quality for engineering design purposes must be evaluated using realistic engineering design problems to gain a measure of its usefulness to concept generation.

1.5 Gallery Method

In the gallery method, individuals of a group begin sketching their ideas silently on sheets of paper. This is referred to as the phase of individual ideation. After a set amount of time, individuals display their sketches as a gallery and discuss their ideas. During the group discussion, the members of the group (a) present their ideas to the group; (b) critically evaluate each other's ideas and (c) modify/eliminate/generate ideas as a group. This is followed by another round of silent individual idea generation and group discussion [1, 2, 4, 9, 19, 44]. Therefore, in the gallery method, there is an alternating sequence of individual ideation and group ideation. A few research refers to the idea generation processes comprised of alternating individual ideation and group ideation as hybrid ideation [25, 44]. A hybrid ideation is an improved group ideation process that first allows individual idea generation followed by group ideation [25]. Linsey and colleagues [18] suggest that group members gain a significant number of ideas by looking at other member's ideas during the idea generation process. Another study highlights the necessity of incorporating tools in group ideation to enhance or leverage the potentials of individual ideation to meet task outcomes [11]. Therefore, both individual and group ideations are essential in an idea generation process. Both individual and group interactions are important in idea generation process [19]. Osborn [21] proposed that "the average person can think up to twice as many ideas when working with a group than when working alone. A combination of group and individual effort is probably the best to generate ideas [18, 22, 36]. Pahl and Beitz [1] suggest using a combination of methods to address design problems where traditional idea generation methods cannot lead to the required goal.

The gallery method can be used to effectively harness the merits of individual and group ideation. As members of a group develop new ideas together, the quality of ideas increases due to a team sharing environment [19]. A study suggests that alternating sequence of individual ideation and group ideation in the gallery method improves the quality of concepts [44]. The process of pooling the individual ideas minimizes idea losses that are incurred in traditional group ideation techniques such as brainstorming [28]. This sequence followed in the gallery method is sometimes referred to as an “individual to group” approach [39]. Another study suggests that the process of generating ideas individually is referred to as divergent task and the evaluation of ideas as a group is referred as a convergent task [45]. Another sequence of ‘group to individual’ can also be utilized for generating ideas. However, past research indicates that its effect on the outcome has not been investigated. Further research needs to be conducted to determine the effect of these sequences and duration of these sequences on the outcome of ideation process. The individual to group approach for generating concepts is considered good because it allows individuals to prepare for the group discussions by first reflecting on their own ideas [39]. However, there is lack of evidence to support that the previously stated limitations of group ideation –free riding, evaluation apprehension and production blocking are eliminated in the gallery method. One promising approach to reduce the recurrence of these limitations during a group idea generation process is through the use of a facilitator. The role of a facilitator during a group ideation process is to employ certain procedures and rules to keep the group members on task and encourage everyone towards achieving the group objectives [21, 24, 36, 42]. The facilitator promotes ideation in groups using wide ranges of techniques such as enforcing ground rules for group members to follow during idea generation, point to rules deferred during discussion, write suggestions on board for discussion, encourage individuals to discuss ideas with little extraneous discussions as possible to avoid digression from objective and provide external stimuli to the group members while generating ideas.[36, 37, 43] Some of the most commonly used ground rules [42-44].comprise of :

1. Defer judgment,
2. Build on ideas of others,
3. One conversation at a time,
4. Stay focused on topic,
5. Encourage wild or creative or novel ideas,
6. Take notes if required
7. Do not interrupt others, wait for your turn"

By establishing the ground rules, the facilitator can limit free riding by allowing each member to contribute to the ideation process. The rules also reduce evaluation apprehension and production blocking by allowing each member of the group sufficient time to discuss ideas, deferring judgment and building on each other's ideas encourages merging individual efforts with group efforts. It also provides individuals with a sense of belonging to the group. Prior to explanation of concepts, the facilitator recommends members to take notes when required during discussion which can be clarified later without interrupting the ongoing discussions; this can moderate the side-effects of having a dominant member in a group. A study suggests that interventions or hints by facilitator function as external stimuli during group ideation when members feel exhausted or experience "stuck in rut" phase [47]. It also suggests that the intervention by facilitator helps generating solutions that might be hard to perceive directly and requires exploration of vast knowledge networks. The facilitator is trained to encourage group members to link and unlink attributes of different concepts to be able to generate new concepts during ideation [39]. The groups with facilitator(s) are found to perform relatively better in generating ideas than the groups without the facilitator(s) [24, 31, 36, 38]. In this research, a facilitated ideation workshop using the gallery method was conducted for three design teams working on an industry sponsored design project to enhance the ideation process, increase the quality of design concepts and improve the group dynamics.

Research Opportunity 2: The limitations of group ideation due to group dynamics- lack of communication and low individual effort can be observed in the gallery method. These limitations can significantly reduce the effectiveness of the gallery method. Past research suggests that the presence of facilitator(s) during group ideation significantly reduces the identified limitations. There is an opportunity to limit the recurrence of these limitations in the gallery method by using facilitator(s). The effect of using facilitator(s) in the gallery method needs to be investigated to increase quality of concepts and improve group dynamics.

1.6 Summary and Identification of Research Opportunities

The following research opportunities have been identified that provide motivation for this research.

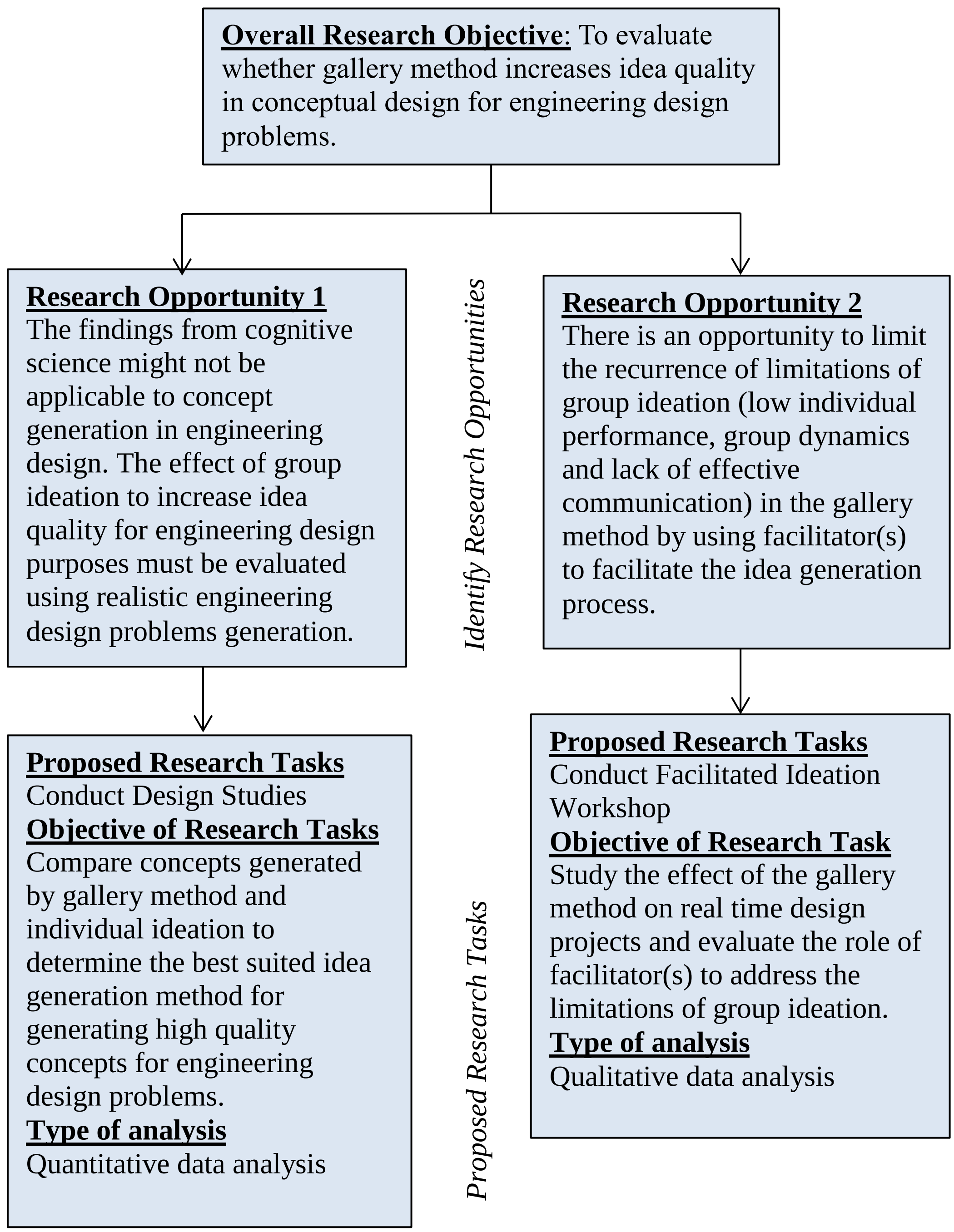

Figure 1.1: An overview of research objective, research opportunities and proposed research tasks

1. The findings from the cognitive science research on the effectiveness of individual ideation may not be applicable to the concept generation in engineering design. The features of both individual ideation and group ideation can be combined to leverage benefits of both in an idea generation process. The effect of group ideation to increase idea quality for engineering design purposes must be evaluated using realistic engineering design problems to gain a measure of its usefulness to concept generation.
2. The limitations of group ideation due to group dynamics- lack of communication and low individual effort can be observed in the gallery method. These limitations can significantly reduce the effectiveness of the gallery method. Past research suggests that the presence of facilitator(s) during group ideation significantly reduces the identified limitations. There is an opportunity to limit the recurrence of these limitations in the gallery method by using facilitator(s). The effect of using facilitator(s) in the gallery method needs to be investigated to increase quality of concepts and improve group dynamics

Figure 1.1 illustrates the identified research objectives, the proposed research tasks to address the research objectives and the type of data analysis in respective research tasks. An overview of the thesis is provided in the following section.

1.7 Thesis Overview

The objective of this research is to evaluate whether the gallery method increases idea quality in conceptual design. The effectiveness of an idea generation technique can be predicted in terms of the key components build into its procedure which enhances the technique to help users meet the goals of idea generation. Depending on the goal of an idea generation technique; whether it is to create large quantity of ideas or to create a few high quality ideas, the effectiveness of an idea generation technique can be defined and evaluated [11]. For an idea generation technique to be effective to meet its goal(s), it must comprise of elements that would mentally simulate users and help them foster the process of idea generation. Figure 1.2 illustrates the thesis overview. An experimental comparison of the gallery method and individual was conducted with two design studies – Design Study I and Design Study II. The objective of the design studies was to determine the best suited method amongst individual ideation and gallery method for generating high quality concepts for engineering design problems. In Design Study I, twelve graduate level students divided into three sets were asked to generate concepts for an engineering design following individual ideation and gallery method. The design concepts were rated on a scale of 0-1-9, the average quality scores were computed and significant sets with highest average quality scores were identified. The Design Study II was conducted to validate results from previous study and to also evaluate the effect of timed sections in the gallery method. In Design Study II, twelve graduate level students divided into three sets were asked to generate concepts for another engineering design problem following individual ideation, gallery method with timed sections and gallery method with non-timed sections. One of the major differences between the two studies (other than the test parameters) is that in Design Study II an exploratory investigation of timed and non-timed sections in the gallery method on the average quality of concepts was also conducted. In the gallery method with timed sections, each round of individual ideation and group ideation was conducted for a specific amount of time. In the gallery method with non-timed sections, the rounds individual ideation and group ideation are not constrained by time. During the gallery method with non-timed sections, the members of a group can immediately proceed to group ideation once individual members have completed generating sketches individually and vice versa. The Design Study II compared the quality of concepts generated by individual ideation and gallery method (both timed and non-timed). The concepts of Design Study II were graded on a 0-1-3-9 scale and average quality score per set were computed. The statistically significant sets were identified to determine the idea generation method with highest average quality scores.

The facilitated ideation workshop was conducted using the gallery method with three undergraduate level student design teams working on Capstone Design Projects. The objective of conducting the workshop was to conduct a preliminary study on the effect of the gallery method on real time design projects where members of a group were required to collaborate and function as a team. Unlike the experimental studies where participants were pseudo groups, the Capstone Design Teams were equivalent to real time design teams. This workshop also helped evaluating the role of a facilitator in addressing the limitations of group dynamics. A survey on the facilitated ideation workshop was conducted at the end of the workshop. A qualitative analysis on the survey responses was performed to obtain results and address the research questions.

Chapter 2 discusses the research framework discussing the research opportunities, research questions and research hypotheses identified in Chapter 1. The Design Study I setup, procedure and results are elaborated in Chapter 3. The Design Study II setup, procedure and results obtained are discussed in Chapter 4. Chapter 5 discusses the facilitated ideation workshop, the setup, procedure and results. The conclusions from the research and scope of future work are discussed in Chapter 6.

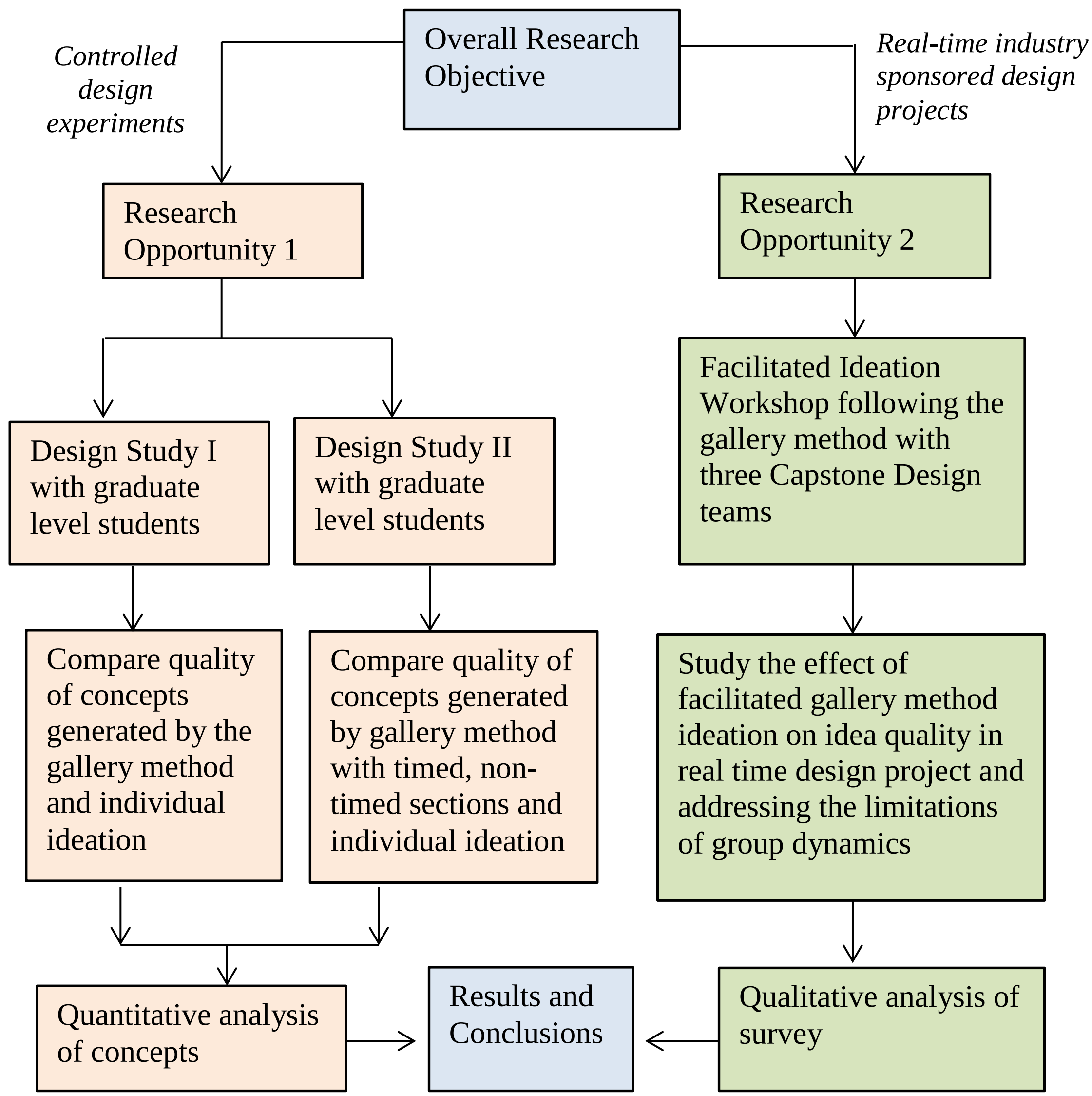

Figure 1.2: Research Overview

Chapter Two
RESEARCH GOALS AND FRAMEWORK

Based on the research opportunities identified in Chapter One, this chapter describes the research objective, related research questions and the corresponding tasks developed to address the research questions.

2.1 Primary Research Objective

The main research objective of this research is to evaluate whether the gallery method increases the average quality of concepts in conceptual design for engineering design problems. Several studies have focused on different metrics to evaluate the design outcomes of idea generation techniques [6, 11, 14, 15, 22, 25, 43, 45–48]. The four major metrics identified to measure the effectiveness of a design idea generation process are novelty, variety, quality and quantity [22, 26, 49].

- *Novelty* is a measure of how unusual or unexpected an idea is as compared to other ideas [29].
- *Variety* is a measure of the explored solution space during the idea generation process [29].
- *Quality* is a measure of feasibility of an idea and how close it meet the design specifications [29].
- *Quantity* is a measure of the total number ideas generated using the idea generation technique [29].

The task of quantitatively characterizing the quality of design outcome is still an open research question in design theory community [54]. Past studies have argued about the relationship between quantity and quality of ideas generated using idea generation techniques [11, 15, 33, 34, 45, 47, 51]. The objective of an idea generation technique is not only to generate a large quantity of ideas but also good quality of ideas. The degree to which a product satisfies customers and can be successfully commercialized depends largely on the quality of underlying concept [4]. Osborn [21] suggested that the more ideas a group produced, greater is the probability that it would produce good ideas. By generating large number of ideas with improved quality, it is expected that it would eventually help designers to generate more exceptional ideas with greater variability thereby increasing the possibilities for variety and novelty in design ideation [7]. However, some research indicates that under varying conditions quantity might not always correlate with idea quality [11, 33]. Some studies indicate that there is a modest causal relationship between quantity and quality but there are other factors that play more important role in determining the number of good quality ideas that a group generates [33, 52]. According to the Bounded Ideation Theory (BIT), the ratio of good quality ideas to the total number of ideas depends on the following factors- the ability of the designers using the idea generation technique, the amount of attention designers devote to the idea generation process, limits of mental and physical exhaustion of the designers, the ability of an individual to work towards achieving group goal(s) while attaining personal goal(s) and possibility of exploration of solution space for generating ideas [15]. Some studies indicate that using a hybrid ideation technique generates high quality of ideas [22, 51].

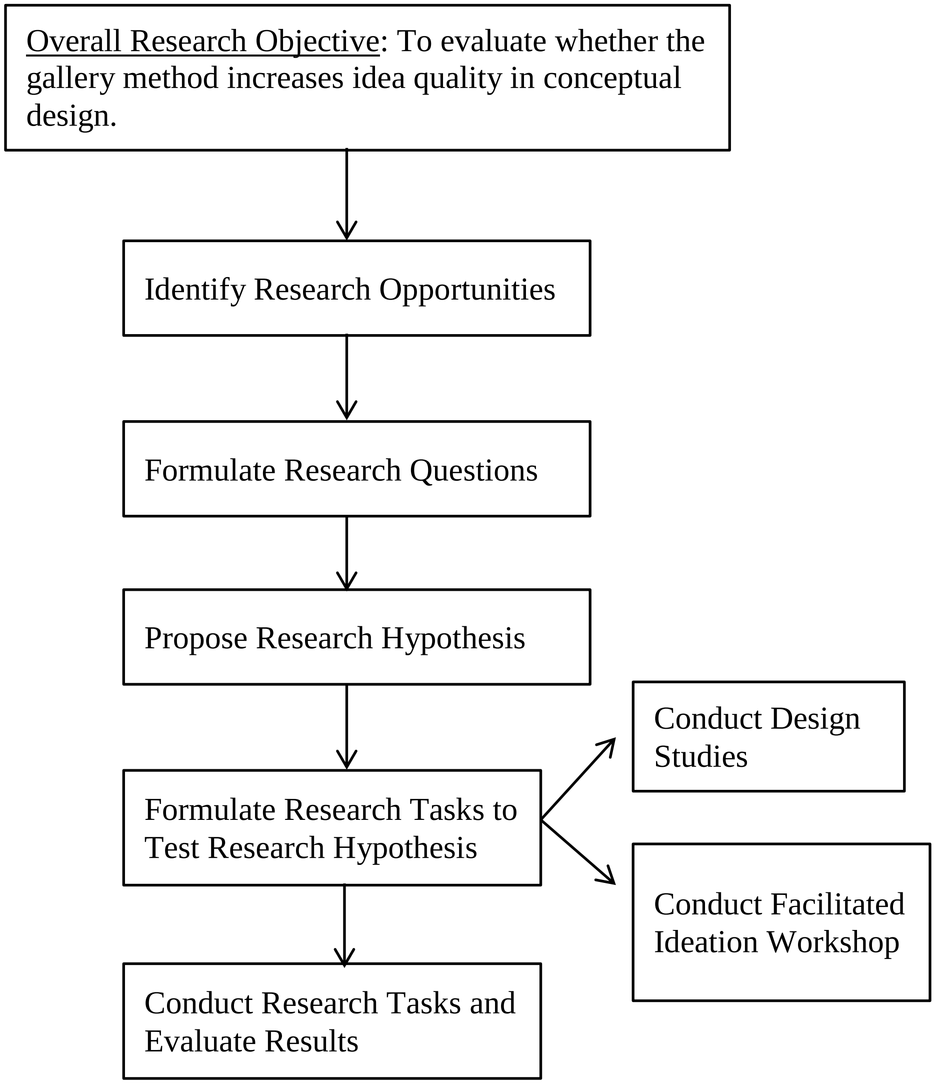

Figure 2.1: An overview of proposed research setup

In our research, both quality and quantity of concepts generated are taken into account; however, it is beyond the scope of the research to evaluate the existence of any relationship between quantity and quality of concepts. The metrics novelty and variety are beyond the scope of the research and hence not taken into account.

2.2 Research Questions

The following research questions are related to the primary research objective.

2.2.1 Research Question 1:

Can the gallery method be more effective than individual ideation for generating high quality concepts for engineering design problems?

There is considerable ambiguity in the findings of past research on the applicability of group ideation for generating high quality concepts as mentioned in Section 1.3. The findings from cognitive science indicate individual ideation superior to group ideation for producing high quality concepts. Past research suggests that limitations of group ideation stated in Section 1.4 reduce its effectiveness in developing high quality concepts. Research findings also indicate that group ideation is commonly used for generating concepts in engineering firms and industrial setup. This shows considerable contrast in results from past research and actual practice of group ideation in industries. To resolve the existing conflict, our research suggests the gallery method as the solution which combines features of both individual ideation and group ideation. The aim of our research is to explore the effect of the gallery method on the quality of concepts. Due to the limitations of group ideation cited in past research and results that support individual ideation, in this research we only compare individual ideation with the gallery method. The comparison between individual ideation and the gallery method is conducted to determine the best suited idea generation method for generating high quality concepts for engineering design and resolve the contrast between past research findings and actual industrial practice of the idea generation methods. The proposed research hypothesis for this research question is stated as follows:

RH1: The average quality of ideas generated by the gallery method is greater than average quality of concepts generated by individual ideation.

2.2.2 Research Question 2:

Do the timed sections of individual and group idea generation in the gallery method affect the quality of concepts generated?

The gallery method first allows individuals of a group to generate concepts individually followed by reviewing the concepts as a group for further development of the concepts. The most important feature of the gallery method is the alternating sequence of individual ideation and group ideation. This first enables individuals to generate concepts on their own followed by a group ideation. During the group ideation section, the individual members can discuss their concepts and collaborate to develop new concepts by modifying or combining two or more existing concepts generated by individuals. As mentioned previously in Section 1.5, there is lack of evidence on the effect of the alternating sequence of individual ideation and group ideation, and the duration of these sections on the quality of concepts. In our research, we investigate the effect of duration of the section in the gallery method on the quality of concepts generated. In the Design Study II, two variations of the gallery method were tested-gallery method with timed sections and gallery method with non-timed sections. In the gallery method with timed sections, the alternating sections of individual ideation and group ideation are time constrained. In the gallery method with non-timed sections, the sections of individual ideation and group ideation are not time constrained. Our research conducts an exploratory investigation of the effect of timed sections of the gallery method on the quality of concepts generated. Due to the exploratory nature of this investigation, the proposed hypothesis for this research question is stated as follows:

RH2: The average quality of concepts generated by gallery method with timed sections and gallery method with non-timed sections are not statistically different.

2.2.3 Research Question 3:

Can the previously identified limitations of group ideation continue to exist in the gallery method when members generate ideas as a group after individual idea generation?

In the gallery method, individual ideation is followed by group ideation. This sequence of alternating sections of individual ideation and group ideation can be performed as many times as required until the objective is achieved. The objective with respect to our research is generating high average quality concepts for engineering design problems. During the group ideation section of the gallery method, the members of a group collectively work on the previously generated concepts during the individual ideation. However, there is a possibility that the previously stated limitations in Section 1.4 can recur during the group ideation section of the gallery method. Under such circumstance, the effectiveness of the gallery method to generate high average quality of concepts would be compromised. Our research intends to reduce the occurrence of these limitations through use of a facilitator during the idea generation phases. The advantages of employing facilitator during idea generation process are discussed in Section 1.5. The proposed hypothesis for this research question is stated as follows:

RH3: A facilitated gallery method reduces the limitations of group ideation and assists in groups to develop high average quality concepts in conceptual design.

2.3 Research Tasks

To address the research questions, two design studies involving graduate mechanical engineering students were conducted to study the effect of the gallery method on the average quality of concepts. In the design studies conducted, the participants were asked to develop and sketch concepts for engineering design problems. The participants were divided into sets, with some sets following individual ideation only and other sets following the gallery method for concept generation. The concepts from each set were collected and graded for quality. The results were then compared to test the research hypotheses. Through these studies, the aim is to identify which of the two idea generation techniques- individual ideation or gallery method is best suited to develop high average quality of concepts for engineering design problems. The results from the studies are used to address RH1.

To study the effect of the gallery method on idea quality of real time design projects and to evaluate the role of facilitator(s) to address the limitations of group dynamics in the gallery method, a facilitated ideation workshop using the gallery method was conducted with senior undergraduate mechanical engineering students working on Capstone Design projects. Unlike the design studies, the facilitated ideation workshop was equivalent to real life industrial idea generation practice. The members of each design team were required to work and collaborate as a team, whereas, such settings are difficult to be achieved in experimental studies. In the facilitated ideation workshop, design teams were assisted to develop conceptual design solutions for an industry sponsored design project using hybrid ideation. The design teams were provided six weeks duration to develop conceptual solutions. The workshop lasted for six weeks. Each team was assigned at least one workshop of 60 minutes per week, on a day chosen by the team as per their convenience. The facilitator employed the gallery method during the workshop for the teams to develop concepts. A survey at the end of the workshop is undertaken to procure feedback on the workshop, use of facilitator to develop concepts and addressing of limitations of group dynamics. The results from the qualitative analysis survey are used to address RH 2. Based on the results from the two design studies and the facilitated ideation workshop, the research hypotheses are tested.

2.4 Research Framework

Table 1.3: Research framework outlining research questions, hypotheses and tasks

Research Questions	Research Hypothesis	Research Tasks
RQ 1: Can the gallery method be more effective than individual ideation for generating high quality concepts for engineering design problems?	**RH1**: The average quality of ideas generated by the gallery method is greater than average quality of concepts generated by individual ideation	Conduct Design Studies with graduate level mechanical engineering students

Research Questions	Research Hypothesis	Research Tasks
RQ 2: Do the timed sections of individual ideation and group ideation generation in the gallery method affect the quality of concepts generated?	**RH2.1**: The average quality of concepts generated by both gallery methods with timed sections and non-timed sections are greater than the average quality of concepts generated by individual ideation. **RH2.2**: There is no difference in the average quality of concepts generated by the gallery method with timed sections and the gallery method with non-timed sections.	Conduct Design Studies with graduate level mechanical engineering students
RQ 3: Can the previously identified limitations continue to exist in the gallery method when members generate ideas as a group after individual ideation?	**RH3**: A facilitated gallery method reduces the limitations of group ideation in the gallery method and assists in developing high average quality concepts in conceptual design	Conduct facilitated ideation workshop using the gallery method with undergraduate level mechanical engineering students working on Capstone Design projects

Table 1.3 describes the research framework of this research. The research questions, proposed research hypothesis and research tasks for this research have been listed. The two design studies were conducted to compare the average quality of concepts generated by individual ideation and gallery method. The overarching objective is to determine the best suited technique to generate high average quality of concepts for engineering problems. The results from these studies will be used to address research questions 1 and research question 2. An outline of the design studies are listed in Table 1.4.

Table 1.4: Outline of Design Study I and Design Study II

	Design Study 1	**Design Study 2**
Objective	To evaluate the average quality of concepts generated by individual ideation and gallery method	To evaluate the average quality of concepts generated by individual ideation, gallery method with timed sections and gallery method with non-timed sections
Participants	12 graduate level mechanical engineering students Three sets each comprising of four participants	12 graduate level mechanical engineering students Three sets each comprising of four participants
Design task	Design a car seating mechanism	Design a can crusher mechanism
Design study protocols	Time allowed: 60 minutes for concept generation and sketching. Materials provided: • Information regarding the study procedure • Presentation on idea generation technique to be followed by each set for concept generation • Templates and accessories for sketching	Time allowed: 60 minutes for concept generation and sketching. Materials provided: • Information regarding the study procedure • Presentation on idea generation technique to be followed by each set for concept generation • Templates and accessories for sketching
Null hypothesis	Average quality of ideas generated by the gallery method is greater than the average quality of ideas generated by individual ideation for engineering design problem.	1. Average quality of ideas generated by gallery method with both timed and non-timed sections are greater than individual ideation for engineering design problem 2. The average quality of concepts generated by gallery method with timed sections and gallery method with non-timed sections are not statistically different

	Design Study 1	Design Study 2
Parameters compared	• Average quality of concepts generated by the gallery method • Average quality of concepts generated by individual ideation	• Average quality of concepts generated by gallery method with timed sections • Average quality of concepts generated by the gallery method with non-timed sections • Average quality of concepts generated by individual ideation
Type of data analysis	• Quantitative	• Qualitative

2.5 Research Scope

The scope of this research is confined to evaluating the effect of the gallery method on quality of concepts during conceptual design, and comparing the suitability of individual and gallery method for generating high average quality of concept(s) for engineering design. The research questions are addressed by completion of the two design studies and facilitated ideation workshop. However, a major challenge has been to procure a large sample size for the studies. Due to constraints of time, participant availability and cost, the studies are conducted using a small sample size. The facilitated ideation workshop served as a preliminary step to investigate the use of facilitated gallery method for assisting real design teams.

The remaining chapters of the thesis will explain in detail about the design studies and the facilitated ideation workshop. The chapters explain the setup, sketching guidelines and deliverables, design problem, analysis and grading of sketches, results and conclusions.

Chapter Three
DESIGN STUDY I

3.1 Overview

Design Study I was developed and conducted to compare the average quality of concepts generated by individual ideation and gallery method for an engineering design problem. Twelve graduate level mechanical engineering students from Clemson University participated in the design study. During the design study the participants were randomly assigned to three sets. The participants of each set were asked to generate and sketch design concepts for an engineering design problem. The total time allotted to each set for concept generation and sketching was sixty minutes. The sketches were then collected and graded by two raters for quality of concepts. An inter-rater agreement using Cohen’s kappa score was computed to establish the reliability of grades. The average quality of concepts per set was computed using the CATMOD function of SAS. The results determined significantly different sets with respect to average quality of concepts across the two groups. The results from Design Study I were used to address Research Question 1. The results indicate that the average quality of concepts generated by gallery method is greater than the average quality of concepts generated by individual ideation.

3.2 Objective

The objective of this study was to determine the best suited idea generation method amongst individual ideation and gallery method in terms of concept quality for an engineering design problem.

Null Hypothesis (RH1): The average quality of concepts generated by gallery method is greater than average quality of concepts generated by individual ideation.

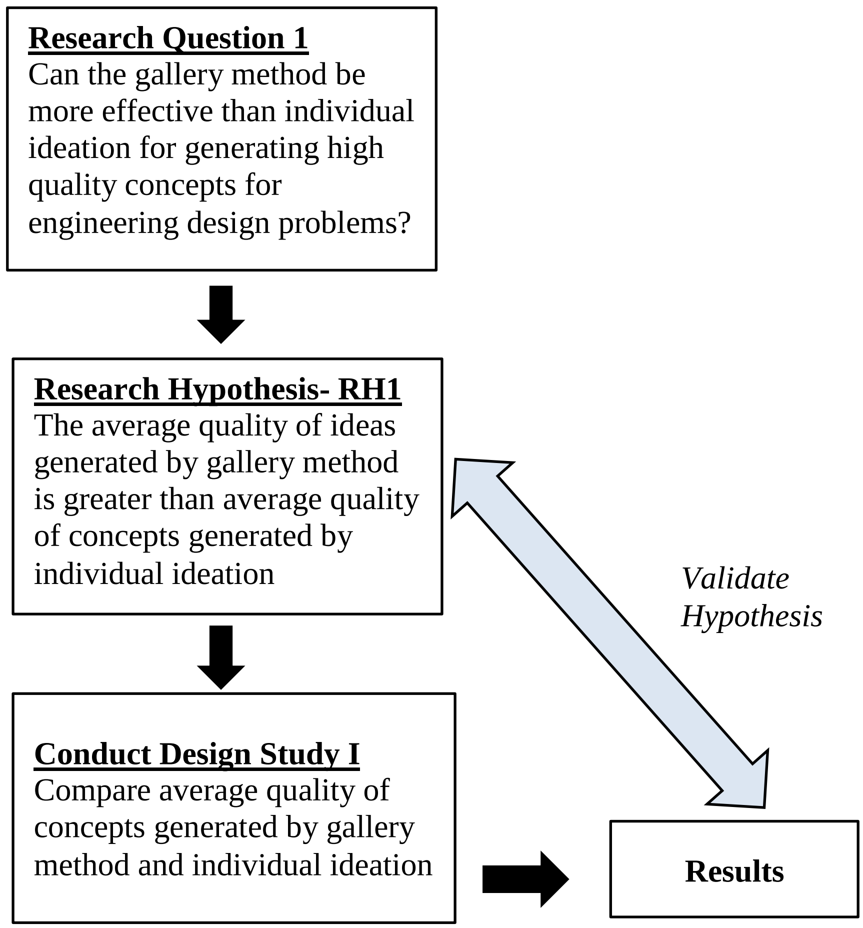

Figure 3.1: Objective of Design Study I

3.3 Participants

The participants for the Design Study I were mechanical engineering graduate level students from Clemson University. A total of twelve participants were involved in this design study. The participants were randomly assigned to three sets, each set comprised of four participants. Each set was required to follow certain time constrained procedures for idea generation referred to as treatments. The purpose of the treatments is to analyze the effect of ideation methods on the average quality of concepts and to avoid design fixation during concept generation. Each set was allotted sixty minutes for concept generation. The treatments used across each set are listed in Table 3.1.

Table 3.1: Treatments followed per set for design study I

Design Study Set	Set Treatment
Set 1	20 minutes of individual ideation, 20 minutes of sketch display, 20 minutes of individual ideation
Set 2	13 minutes of individual ideation, 10 minutes of sketch display, 13 minutes of individual ideation, 10 minutes of sketch display, 13 minutes of individual ideation
Set 3	15 minutes of individual ideation, 15 minutes of group discussion, 15 minutes of individual ideation, 15 minutes of group down- selection of ideas

The participants for the study were selected due to the following reasons:

a. The voluntary participation of the participants for the design study.
b. All the participants had background of idea generation methods as part of their course work which enabled them as suitable candidates for the study.

Previous research suggests that extrinsic incentives are known to limit the creative behavior [25], therefore, no explicit incentives or compensation was provided for participation in this design study. The participation in the design study did not hold any consequence to the academic credits of the participating students. The voluntary participation can have effect on the results of the study based on the factors for their participation and motivation at the time of the study [53, 54, 55]. A few motivation factors responsible for voluntary participation are cited below [54, 55]:

Table 3.2: Factors responsible for voluntary participation

Factors	**Conceptual Definition**	**Sample**
Values	The individual volunteers in order to express or act on important values like humanitarianism.	I feel it is important to help others.
Understanding	The volunteer is seeking to learn more about the world or exercise skills that are often unused.	Volunteering helps me learn through direct, hands-on experience.
Enhancement	One can grow and develop psychologically through volunteer activities.	Volunteering makes me feel better about myself.
Career	The volunteer has the goal of learning career-related experience through volunteering.	Volunteering can help me to get my foot in the door at a place I would like to work.
Social	Volunteering allows an individual to strengthen his or her social relationships.	People I know share an interest in volunteering for this activity.
Protective	The individual uses volunteering to reduce negative feelings, such as guilt or to address personal issues.	Volunteering is a good escape or break from my issues.

In the design studies conducted during this research, voluntary participation of the participants can be explained through the factors listed in Table 3.2. The motivation levels of the participants would vary based on the factor(s) responsible for participation. However, it is beyond the scope of this research to investigate the motivation levels of the participants of the design studies.

3.4 Problem Statement

The following problem statement was given to the participants of Design Study I:

"Design a car seating mechanism that will place the occupant in the desired travel window (see below). The car seat will have to facilitate full upward and full forward movement along the trajectory (H-point) to accommodate short users and full rearward and full backward movement to accommodate tall users." The seat has to adhere to the following requirements:

- *The h-point travel window.*
- *The total length of the horizontal motion required of the mechanism is 10.6 in.*
- *The total length of the vertical motion required of the mechanism is 4 in.*
- *The amount of effort required to adjust the seat must be minimal.*
- *Must not deform elastically to unacceptable extent under normal operating conditions.*
- *Must not rattle (shaking of joints) under normal operating conditions thereby avoiding noise.*
- *Mechanism can be manually or electronically controlled.*

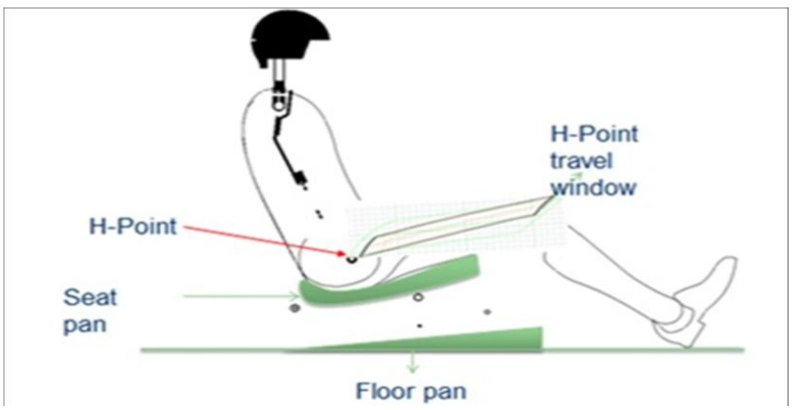

Figure 3.2: Design Study I problem statement with list of requirments and an illustrative figure

The participants were provided an illustrative figure (Figure 3.2) to aid better understanding of the design problem. The problem statement given to the participants was not explicitly differentiated into functional and non-functional requirements. However, during the analysis of concepts these were categorized into functional and non-functional requirement (See Table 3.3).

Table 3.3:List of functional and non functional requirements of pilot study design problem statement

Requirement	Type of requirement
Horizontal motion of seat	Functional (FR1)
Vertical motion of seat	Functional (FR2)
Locking the seat	Functional (FR3)
No elastic deformation	Non-Functional (NFR1)
Minimum noise during operation	Non-Functional (NFR2)
Mechanism to operate the seat (manual or electronic operation)	Non-Functional (NFR3)

The functional requirements are defined as the requirements that are vital for a system or mechanism. The functional requirement specifies a function that a system component must be able to perform whereas the non-functional requirements are any other requirements than the functional requirements. The functional requirements capture the nature of the interaction between the component and its environment and non-functional requirements restrict the type of solutions one might consider as they are often called as the constraint. The non-functional requirements can be quality requirements which describe the wanted qualities of the product that are not directly related to the functional requirements [59].

3.5 Design Study I Procedure

The design study was conducted separately and independently for each study set. The total time allotted for the study to each set was sixty minutes. The participants of the three study sets were required to generate and sketch concepts for a common engineering design problem. The participants were informed that their participation for the design study was not mandatory and they would not be penalized for withdrawal from the design study. A fifteen minutes presentation on idea generation methods relevant to each study set was provided prior to the commencement of the study. The presentation also explained the objective for each study set, detailed description of the problem statement, sample illustrations of good and bad concept sketches to help participants understand the expectations from concept generation. An additional ten minutes were provided to clarify the instructions and address any questions regarding the problem statement. Each participant was provided with the following materials prior to the study:

- A hard copy of presentation relevant to each set.
- Problem statement and list of requirements (single page)
- Sketch templates to draw concepts. The sketch template included sketching space and a text box to provide brief textual description of the concept.
- The sketch templates were subtlety coded for recording the number of concepts generated per participant without revealing any information regarding the participant identity.
- The participants were informed that the sketches are coded to estimate the number of concepts generated per participant and would not reveal information related to identification of the participant. The coded templates also helped participants to modify previously generated concepts by mentioning the code of the previous concept sketch on the new template.
- Pencils and erasers as sketching accessories.

The participants were asked to limit one concept per page, annotate sketches and provide brief textual description of the concept. They were informed that the combination of sketch and textual description must be provided for reviewers to analyze and understand the concepts. At the end of the presentation, the participants were asked to generate and sketch conceptual ideas for the engineering design problem. The procedure followed by each study set is listed in Table 3.1 The participants of study Set 1 and Set 2 generated concepts independently following the respective treatment procedure per set. The participants of study Set 3 generated concepts as a group following the gallery method. The participants of study Set 1 were asked to generate and sketch concepts following individual ideation for twenty minutes followed by twenty minutes of sketch display and last round of individual ideation for twenty minutes. During the sketch display, all the participants were asked to display their concept sketches as in the gallery method without any discussions. The purpose of the sketch display was to minimize design fixation, provide stimulus to generate more concepts and expose the participants to design concepts other than their own. The participants of study Set 1 were not allowed to interact or discuss their concepts with each other. This was done to maintain the rule of individual ideation where designers generate concepts individually without any explicit direct communication.

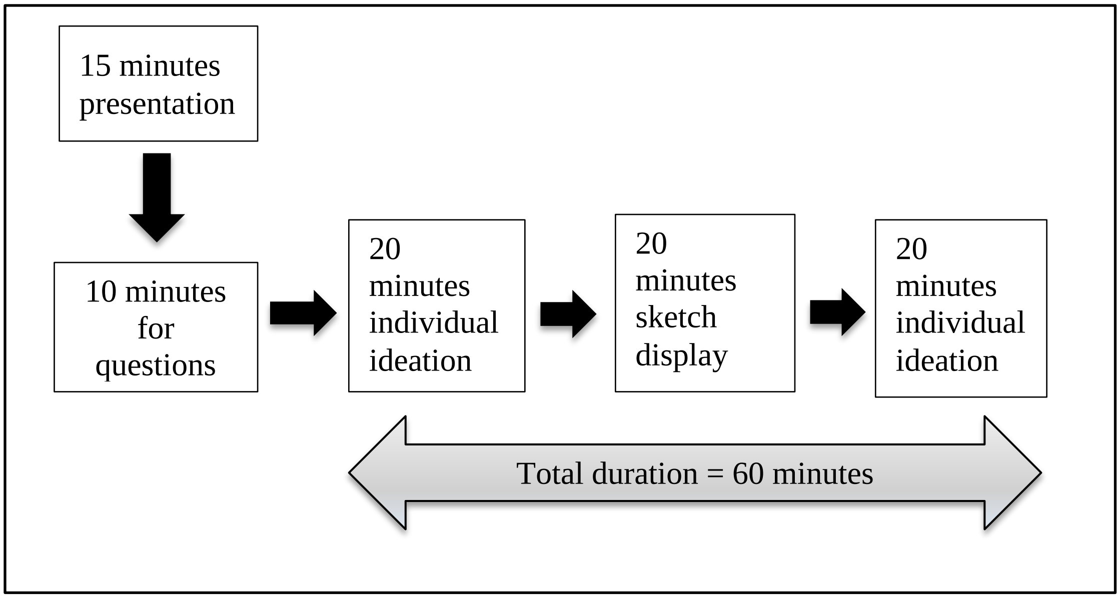

Figure 3.3: Treatment followed by Set 1 in Design Study I

The participants of study Set 2 were asked to generate concepts in the same manner as study Set 1 with the exception of times allotted for individual ideation and sketch display (see Figure 3.4). The participants started with thirteen minutes of individual ideation followed by 10 minutes of sketch display. This pattern was repeated once more and concluded with last thirteen minutes of individual ideation. The purpose of sketch display in study set was same as of study Set 1. There was interaction or discussion allowed amongst the participants during the study. The participants independently generated concepts during the study. The primary difference between study Set 1 and Set 2 is the time allotted to each study for individual ideation and sketch display. This was done to determine the whether the amount of time or number of ideation rounds had any effect on the average quality of concepts generated during individual ideation.

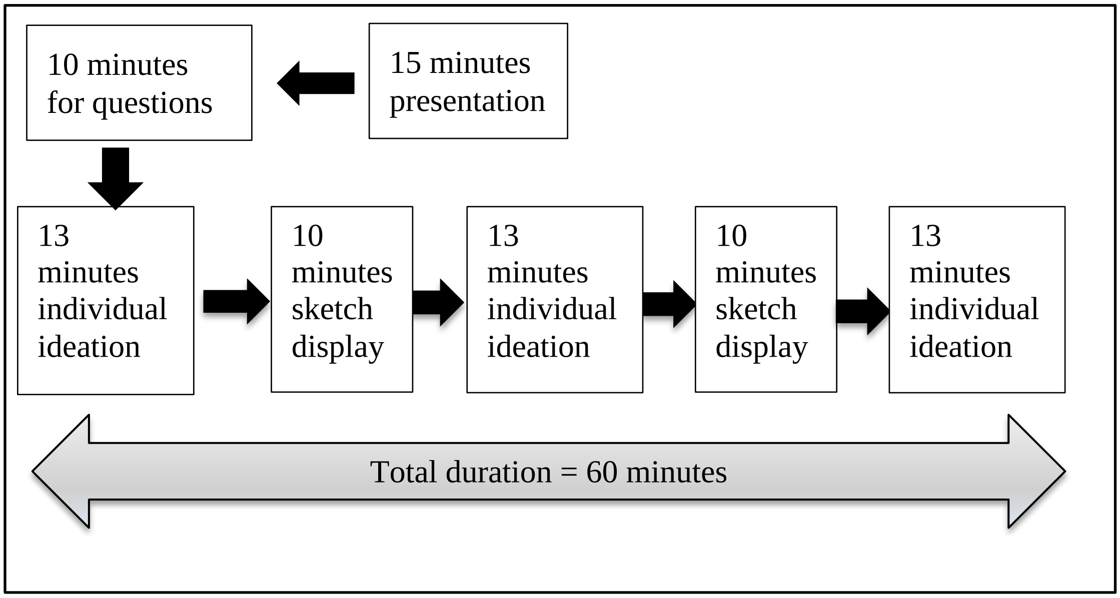

Figure 3.4: Treatment followed by Set 2 in Design Study I

The participants of study Set 3 were asked to follow the gallery method to generate design concepts. The participants were informed to generate these concepts as a group following the procedure (see Figure 3.5) of hybrid ideation. The participants of this set first generated concepts individually followed by group ideation. During the group discussion, the participants were allowed to display their sketches as in gallery method and explain the concepts to the other members of the group. The group discussion also allowed persistent questioning, negation, forward/ backward iteration steps, down-selection of ideas and uninhibited communication to generate widest possible solution concepts for the design problem as a group. The group ideation was followed by another fifteen minutes of individual ideation where participants were allowed to modify their concepts or generate new concepts based on the feedback from previous group discussion. This was concluded by last fifteen minutes of group ideation. During the last round of group ideation, the members were advised to down-select concepts which the group considered as the best solution(s) to the design problem.

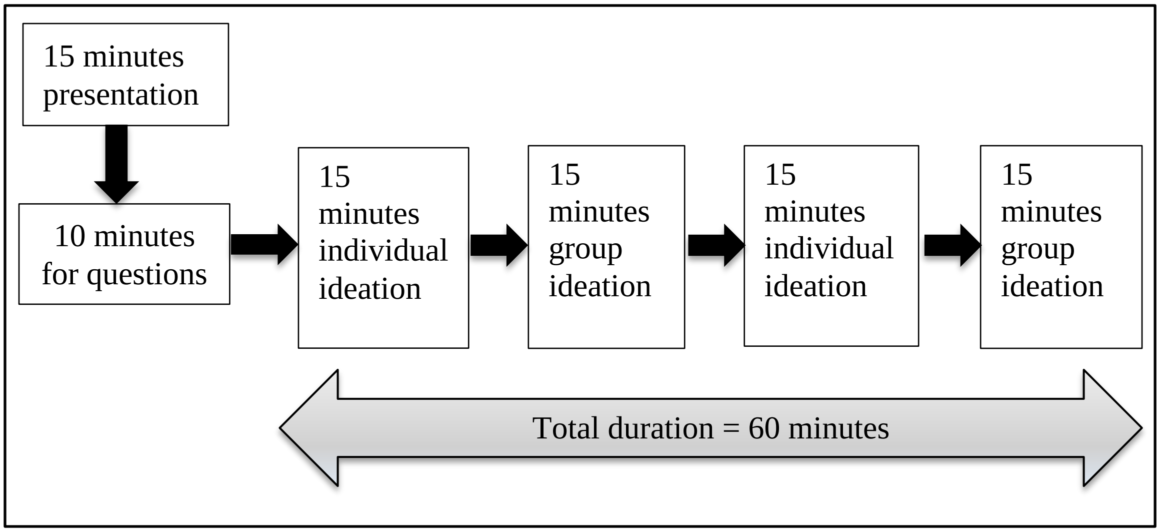

Figure 3.5: Treatment followed by Set 3 in Design Study I

At the end of the study, all the sketches were collected from each study set. All the concepts generated were graded for quality. This was done to avoid skewing of data on account of presence of participants in any of the sets with the ability to consistently generate high quality concepts, thereby artificially skew the data.

Therefore, in Set 1 and Set 2, there was no explicit direct communication between the participants. The participants of Set 1 and Set 2 generated concepts using individual ideation. The participants of Set 3 were allowed to have discussion during group ideation section of the gallery method, therefore, it is considered as different from procedure followed by Set 1 and Set 2.

3.6 Analysis and Concept Evaluation

The analysis of the concepts led to the following observations:

- The participants concentrated on sketching design concepts to address all the functional requirements and two out of three non-functional requirements.
- The non-functional requirement -‘seat must not deform elastically to unacceptable extent under normal operating conditions’ was not addressed by any participant.
- Seventy five percent of the participants sketched concepts of the subsystems rather than the complete seating mechanism in the template provided.

Based on the above observations, the following guidelines were established for concept evaluation:

- The design concept must meet at least one of the functional requirements to be evaluated otherwise it shall be graded a zero.
- If subparts of a mechanism are sketched separately on different sketch templates, they will be considered and graded as a single concept. Some participants drew subparts of the same mechanism (addressing one requirement at a time, for instance, mechanism for horizontal motion on one template, locking mechanism of the same concept on another template) on multiple templates. Under such circumstances, the subparts will be collectively graded as a single concept.
- Incomplete sketches or missing information inhibiting the concept’s understanding will be graded as zero.

The concepts were graded by two independent raters using two different scales. First the concepts were graded on a scale of 0-1, where ‘0’ means absence of a particular requirement and ‘1’ means presence of a requirement in the concept. This helped eliminating incomplete solutions and the design concepts that failed to address at least one of the functional requirements. Two out of thirty two sketches were eliminated after grading the sketches on 0-1 scale. This was succeeded by grading the concepts using a ‘0-1-3-9’ scale. The rubric for the scale 0-1-3-9 is listed in the Appendix. The non-functional requirement -‘seat must not deform elastically to unacceptable extent under normal operating conditions’ was not addressed by any participant, therefore, was excluded from the rubric.

3.6.1 Inter-Rater Agreement Results

An inter-rater agreement score (IRA) was calculated by determining the Cohen’s kappa value. There must be substantial consensus between the raters in order to obtain agreeable results. The rubric was reviewed by both the raters to establish understanding of it prior to grading the concepts. The raters also practiced grading sketches to be trained on the rubric. With substantial IRA scores, the conclusions will have greater value since it is the opinion of more than one rater. The equation for Cohen’s kappa value is given below:

$$k = \frac{\Pr(a) - \Pr(e)}{1 - \Pr(e)}$$

where $\Pr(a)$ is the relative observed agreement among raters and $\Pr(e)$ is the hypothetical probability of chance agreement [54, 55]. The interpretation of inter-rater agreement based on the Cohen’s kappa value is shown in Table 3.4 [61].

Table 3.4:Cohen's kappa value interpretation

Cohen's Kappa Values	Agreement
Less than 0	Less than chance agreement
0.01 – 0.20	Slight agreement
0.21 – 0.40	Fair agreement
0.41 – 0.60	Moderate agreement
0.61 – 0.80	Substantial agreement
0.81 – 0.99	Almost perfect agreement.

Due to the low IRA scores after three iterations (see Table 3.5), the rubric scale was changed to a 0-1-9 and concepts were graded using the refined scale. The rubric for the refined scale 0-1-9 is listed in

Table 3.6. The number of iterations for concept evaluation is denoted by I1, I2 and I3. At this point, it is important to clarify that the scales were chosen to evaluate the concepts on absent, low, medium and high scale. The numerical scores of 0-1-3-9 were applied for computing the numerical analysis of the concept quality [59, 60]. Due to the low IRA scores, the scale was modified to absent, low and high scale using the 0-1-9 numerical scoring.

Table 3.5: Inter-rater agreement scores with 0-1-3-9 scale

Iteration	**Requirement**					
	FR1	*FR2*	*FR3*	*NFR1*	*NFR2*	*NFR3*
I 1	0.28	0.31	0.18	0.55	0.52	0.30
I 2	0.41	0.40	0.57	0.55	0.57	0.55
I 3	0.43	0.32	0.47	0.58	0.55	0.48

Table 3.6: Design study I refined rubric with 0-1-9 scale

Requirement	Absent (0)	Low (1)	High (9)
Full Horizontal movement (FR1)	No mechanism present	Bad /unstable mechanism, impossible to construct or install/ unstable components. Needs additional information regarding the mechanism or components or needs supporting elements.	Efficient mechanism or feasible mechanism that can work with some modifications, with information on most components of the mechanism. Additional information on mechanism might be required.
Full Vertical movement (FR2)	No mechanism present	Bad/ unstable mechanism, impossible to construct or install with unstable components. Requires additional information on components or mechanism or needs supporting elements	Efficient mechanism or feasible mechanism that can work with some modifications, with information on most components of the mechanism. Additional information on mechanism might be required.
Locking the seat (FR3)	No locking mechanism present	Bad or unstable mechanism. Requires more information on mechanism or components or additional supporting elements.	Specific features used in the mechanism to lock and secure the seat. Additional changed might be required.
Noise under normal operating conditions (NFR1)	Requirement not addressed.	Very high rattling or noise of components or due to moving of components	Negligible or very low rattling or noise

Requirement	Absent (0)	Low (1)	High (9)
Ease to move seat in horizontal direction (NFR2)	No features or components specified to address the requirement.	Complex, difficult to operate and requires high to medium manual effort - Pulling the seat manually	Simple and easy to operate with minimal effort- switch or knob like features present.
Ease to move seat in vertical direction (NFR3)	No features or components specified to address the requirement.	Complex, difficult to operate and requires high to medium manual effort - Pulling the seat manually	Simple and easy to operate with minimal effort- switch and knob like features present.

The IRA scores using the refined rubric with 0-1-9 scale were computed. The IRA scores changed from fair to substantial agreement using the refined scale are listed in Table 3.7. The final scores from I3 were used as final scores for the concept evaluation and are listed in Appendix A3. Additionally, an intra-rater agreement was also computed using the revised scale. The intra-rater agreement scores were computed to determine how consistent the raters were in grading the concepts. The intra-rater agreement per rater was computed using the evaluation scores from the last two iterations -I2 and I3. The average of intra-rater agreement scores computed using the iterations are listed in Table 3.8.

Table 3.7: Inter-rater agreement scores with 0-1-9 scale

Iteration	**Requirement**					
	FR1	*FR2*	*FR3*	*NFR1*	*NFR2*	*NFR3*
I1	0.40	0.49	0.40	0.65	0.45	0.50
I2	0.70	0.73	0.77	0.67	0.70	0.70
I3	0.70	0.75	0.71	0.67	0.70	0.75

Table 3.8: Intra-rater agreement scores with 0-1-9 scale

Rater	Requirement					
	FR1	*FR2*	*FR3*	*NFR1*	*NFR2*	*NFR3*
R1	0.67	0.61	0.81	0.73	0.90	0.91
R2	0.75	0.80	0.77	0.85	0.93	0.90

3.6.2 Statistical Data Analysis

An ordinal data set was obtained after the concepts were graded using the refined scale. An ordinal data set is non-parametric in nature; it cannot be analyzed directly using the parametric statistical tools. A non-parametric data is not drawn from any distribution. Therefore, the data set for this study cannot be assumed to be drawn from a normal distribution. Hence, the statistical tools used to evaluate normal distribution samples cannot be applied here for statistical analysis. The average quality of concepts for each requirement across different sets is calculated using CATMOD function of SAS. The CATMOD function blocks the effect of ranking used for grading the concepts, meaning - the average or mean of the data is sensitive to the number of 0s, 1s and 9s of the scale. The presence of a few 9s in a data sample primarily comprising of 0 and 1 can significantly skew the mean of the data set. A rating of 0 (absence of a requirement being addressed) is very different from a rating of 1 (poor concept solution) which in turn is very different from a rating of 9 (excellent concept solution). Therefore, to avoid the skewing of data, weighted means (average quality of concepts) are calculated for each requirement per set. The CATMOD function also performs a linear model analysis by weighted means for each functional and non- functional requirement per study set and compares the weighted means of each study set across the requirements to identify significantly different sets.

The level of significance for Design Study I is 10% due to the exploratory nature of the study, degree of control in design criteria and power of test- sample size.[64] The degree of control criteria suggests that under controlled conditions, small error rates (0.01 or 0.001) should usually accompany large N's whereas large error rates (0.10 or 0.05) should be used for small N's [64] [65]. The average quality of design concepts per requirement computed using CATMOD function and the total number of concepts generated by each study set are listed in Table 3.9 and explained as follows:

The average quality score of concepts generated by Set 1 to address functional requirement 1 (FR1) was 3.9. The Set 2 had an average quality score of 5.4 for addressing FR1. Similarly, the Set 3 secured an average quality score of 6.7 for addressing the FR1. Likewise, the average quality score of each study set for addressing the requirements are listed.

Table 3.9: Average quality of concepts per requirement across design study I sets

Design study set	**Total Number of concepts**	**Requirement**					
		FR1	*FR2*	*FR3*	*NFR1*	*NFR2*	*NFR3*
1	10	3.9	4.2	3.6	3.4	7.2	7.0
2	7	5.4	2.1	2.5	2.0	7.1	7.1
3	15	6.7	6.8	6.0	3.1	6.0	6.1

The statistically significantly study sets are identified with p-value less than 0.10. When the statistically significant study sets were identified, their weighted means were compared to determine the set with highest average quality of concepts for the respective requirement. The statistically significant study sets for each requirement with the corresponding p-value and average quality of design concepts are listed in Table 3.10. For the functional requirement FR1, Sets 1 and 3 are identified as contrasting sets with p-value less than 0.10. This indicates that the average quality score of Set 1 and Set 3 are significantly different and by comparing the average quality scores of the two sets, Set 3 is identified with higher average quality score. Based on the CATMOD analysis, there were no statistically significant user study sets for any of the non-functional requirement. The statistically significant user sets were only identified for all the functional requirements.

3.7 Results

The following results are obtained from the CATMOD analysis of the data (See Table 3.10) for design study I: (Refer Table 3.1 for set treatments)

Table 3.10: Statistically significant Design Study I sets identified by CATMOD

Requirement	Contrasting Sets	p-value	Set with highest average quality of concepts
FR1	Set 1 vs. Set 3	0.08	Set 3 = 6.7
	Set 3 vs. Set 2	0.03	Set 3 = 6.7
FR2	Set 1 vs. Set 3	0.09	Set 3=6.8
	Set 2 vs. Set 3	0.00	Set 3=6.8
FR3	Set 2 vs. Set 3	0.07	Set 3=6.0

The Set 3 (gallery method) generated the maximum number of design concepts shown in Table 3.9. For requirement FR1, the average quality of concepts generated by Set 3 was found to be greater than the average quality of concepts generated by Set 1 and Set 2. Similarly, the average quality of concepts generated by Set 3 was found to be greater than the average quality of concepts generated by Set 1 and Set 2. The average quality of concepts generated by Set 3 was greater than the average quality of concepts generated by Set 2 for addressing the requirement FR3. The Set 1 and Set 3 were not identified to be statistically different for this requirement. This indicated that there was no difference in average quality of concepts generated by Set 1 and Set 3 for addressing this requirement. The study set 3 has the highest average quality of concepts than Set 1 and Set 2 for addressing the functional requirements – FR1 and FR2 because as shown in Table 3.10, both study Set 1 and Set 2 are identified statistically different from study Set 3 with p-values less than 0.10. Because these are statistically different, the weighted means for the sets are compared to determine the set with highest weighted means. The Set 3 was identified with the highest weighted means or average for addressing FR1 and FR2. The Set 3 design concepts have greater quality than design concepts generated by Set 2 for FR3. However, there was no difference identified in the average quality of design concepts for FR3 between Set 1 and Set 3.

3.8 Summary

The results from Design Study I indicate that gallery method generated higher average quality of concepts than individual ideation for addressing the functional requirements of an engineering design problem. There was no difference in the average quality of concepts generated by the sets for addressing any of the non-functional requirements. This indicated that the average quality of concepts across the study sets for the non-functional requirements was same. This also indicated that functional requirements were quickly perceived for generating concepts as opposed to non-functional requirements for the engineering design problem used in this study. There was no difference in the average quality of concepts generated by design study Set 1 and Set 2 for addressing functional and non-functional requirements. This indicated that the amount of time allotted for individual ideation and sketch display in individual ideation did not have any significant effect on the average quality of concepts generated. There is lack of evidence to state the effect of gallery method on the average quality of concepts for addressing the non-functional requirements. There were no contrasting study sets identified for addressing the non-functional requirements indicated that average quality of concepts generated by all design study sets for addressing the non-functional requirements is same. As stated previously, it is difficult to discern the quality of solutions for non-functional requirements at the conceptual design stage. Therefore, the results support the null hypothesis for functional requirements. **RH1 is supported to be true for functional requirements.**

The small sample size of this study limits the validity of the results. A second design study was conducted to test the repeatability of results from Design Study I under varied experiment settings (using a new problem statement, modified set treatments and participants).

Chapter Four
DESIGN STUDY II

4.1 Overview

The objective of the Design Study II was to compare the average quality of concepts generated by gallery method and individual ideation for an engineering design problem. The Design Study II was conducted to test the repeatability of Design Study I results for different test parameters such as – a different engineering design problem, modified set treatments and new participants. In addition to the comparison between gallery method and individual ideation, Design Study II also compared gallery method with timed sections and gallery method with non-timed sections to determine the effect of timed sections of the gallery method on the quality of concepts generated. In the gallery method with timed sections, the sections of individual ideation and group ideation were timed constrained. In the gallery method with non-timed sections, sections of individual ideation and group ideation were not time constrained. The participants of the gallery method with non-timed sections were allowed proceed to group ideation after individual members were finished with individual ideation and vice versa. The gallery method with non-timed sections was provided with an overall time limit for idea generation; however, each section of individual ideation and group ideation were not constrained by time. As stated earlier in Section 1.5, further research needs to be done on the effect of the duration of individual ideation and group ideation followed in the gallery method. Therefore, the gallery method with timed sections and gallery method with non-timed sections were compared in this study.

There were three study sets used during this study. Similar to Design Study I, all the sets of this study were asked to develop and sketch concepts for an engineering design problem. The concepts were evaluated by two raters and inter-rater agreement scores using Cohen's kappa were computed. The average quality of concepts per set was evaluated using CATMOD function of SAS. The results from Design Study II were used to address research question 1.

4.2 Objective

The objective of conducting the Design Study II was same as the Design Study I. In design Study II, the average quality of concepts generated for an engineering design problem through individual ideation and gallery method were compared to determine the best suited idea generation method. In this study the average quality of concepts generated by individual ideation, gallery method with timed sections and gallery method with non-timed sections were compared. The results from this study will address Research Question 1. The results from this study will further shed light on the exploratory investigation of timed and non-timed sections of gallery method and will address Research Question 2. The two null hypotheses for this study are stated as follows:

Null Hypothesis 1 (RH2.1): The average quality of concepts generated by both gallery method- with timed sections and non-timed sections are greater than the average quality of concepts generated by individual ideation.

Null Hypothesis 2 (RH2.2): There is no difference in the average quality of concepts generated by gallery method with timed sections and gallery method with non-timed sections.

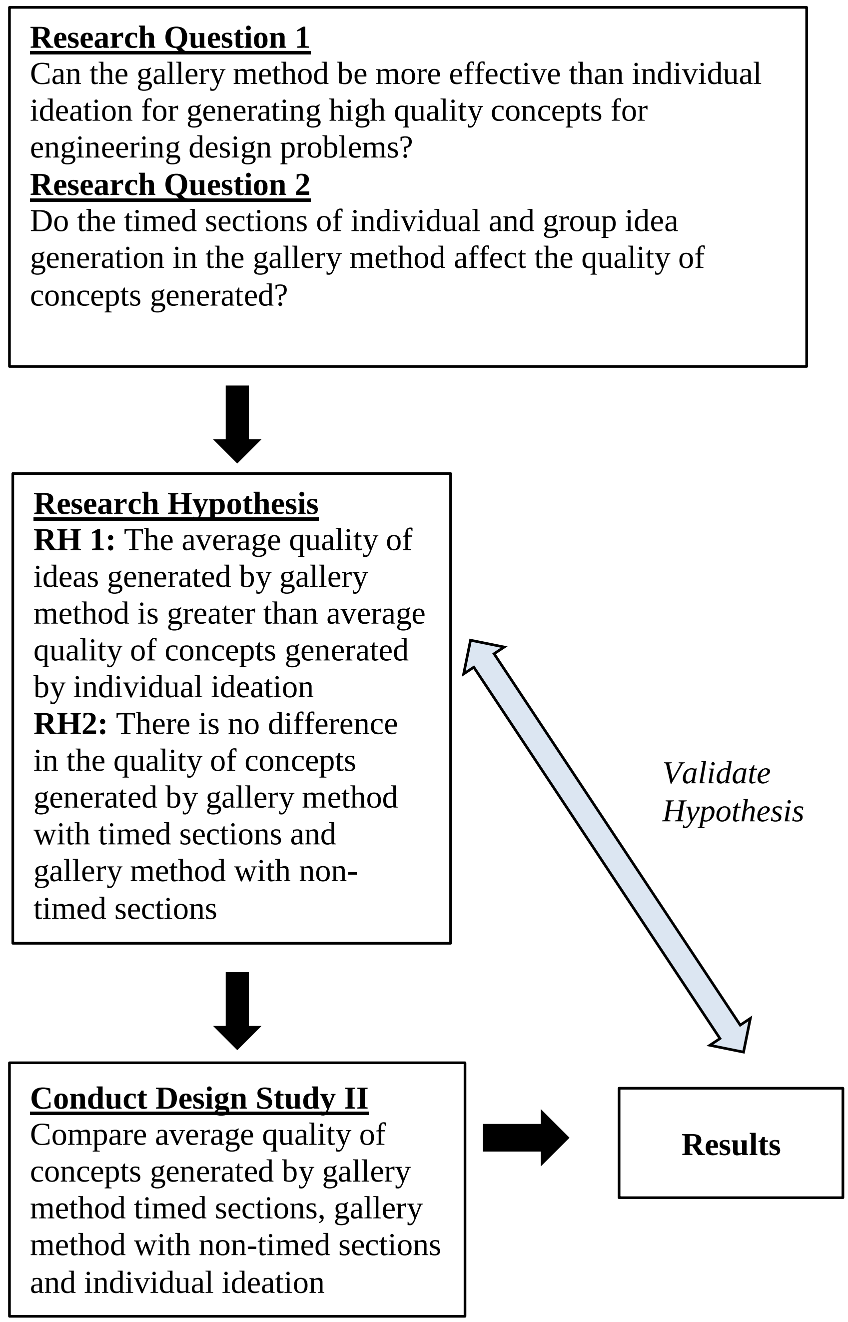

Figure 4.1: Objective of Design Study II

4.3 Participants

The participants for this study were twelve mechanical engineering graduate level students of Clemson University. Similar to the Design Study I, the participants of this study were randomly assigned to three sets, each set comprised of four participants. Two sets were provided sixty minutes for concept generation and one set was given five days for concept generation. The sets were asked to follow treatments designed to avoid design fixation during concept generation. The treatments followed by sets in Design Study II are different from Design Study I. The treatments followed by each set in this study are described in Table 4.1.

Table 4.1: User Study sets and treatments used in Design Study II

Design Study Set	Set Treatment
Set A	15 minutes of individual ideation, 15 minutes of group discussion, 15 minutes of individual ideation, 15 minutes of group discussion. (Gallery method with timed sections)
Set B	Total time allotted for idea generation – 60 minutes (Gallery method with non-timed sections)
Set C	Total time allotted for idea generation – 5 days (individual ideation)

The participants of Set A and Set B were provided sixty minutes to generate and sketch concepts for an engineering design problem. The participants of Set A were asked to generate concepts using the gallery method with timed sections. The participants of Set B were asked to generate concepts using the gallery method with non-timed sections. The Set C participants were asked to generate concepts using individual ideation and were provided five days for concept generation. The Set C participants were provided longer time duration for concept generation because increased time for idea generation can stimulate thoughts useful for the idea generation process [2, 6, 63],. Ideas can come to designers they let the design problem simmer in their thoughts [66]. In addition, to avoid duration of the idea generation process limit the quality of concepts generated by an individual, the participants of Set C were given five days to generate concepts. The participants of individual ideation were provided with an experiment package containing the engineering design problem, list of deliverables, sketch templates for drawing sketches of the ideas, sample sketches depicting examples of good, bad and poor ideas. Prior to giving the experiment package to the individual sets, the content of the package was explained. The participation for this study was voluntary and no explicit incentives or compensation was provided for participation.

4.4 Problem Statement

An engineering design problem was provided to the three sets of the Design Study. Figure 4.2 illustrates the engineering design problem statement with the list of requirements given to the participants of Design Study II. The requirements of the mechanism were not differentiated into functional and non-functional requirements when it was given to the participants during the study. The participants were asked to address all the requirements. However, for the analysis of the concepts it was required to categorize the requirements as listed in Table 4.2.

Design a mechanism to accept used aluminum drink cans and store the crushed ones for subsequent recycling. The original height of a can lies between 115 and 153mm, typical diameter is 65mm and the average mass is 0.02kg. The maximum force required to crush a can is 2kN.

- *The mechanism should perform the following:*
- *To accept can from an individual and store the crushed can.*
- *The mechanism must be portable.*
- *The stored crushed cans will be collected for recycling; the crushed cans storage must to be accessible.*
- *To reduce storage space, the can is to be crushed to a height of approximately 15mm.*
- *The mechanism must be safe to operate.*
- *The mechanism can be manually or electronically controlled.*

Figure 4.2: Design Study II problem Statement and list of requirements

Table 4.2: List of requirements in design problem used for Design Study II

Requirement	Type of requirement
Accept can (s)	Functional requirement (R1)
Crush can(s)	Functional requirement (R2)
Store the can(s)	Functional requirement (R3)
Reduce storage space -height of crushed can(s) is 15mm	Functional requirement (R4)
Mechanism can be manually or electronically operated	Functional requirement (R5)
Stored can(s) must be accessible	Non- Functional requirement (R6)
Mechanism must be safe to operate	Non- Functional requirement (R7)

Requirement	Type of requirement
Mechanism must be portable	Non- Functional requirement (R8)

4.5 Design Study II Procedure

The study was conducted separately and independently for each study set. The total time allotted to sets A and B for the study was sixty minutes. The set C was given five days for the study. The participants of the three study sets were required to generate and sketch concepts for a common engineering design problem. The participants were informed that their participation for the design study was not mandatory and they would not be penalized for withdrawal from the design study. Similar to Design Study I protocol, for this study, a fifteen minutes presentation on idea generation methods relevant to each study set was provided prior to the commencement of the study. The presentation explained the objective for each study set, detailed description of the problem statement, sample illustrations of good and bad concept sketches to help participants understand the expectations from concept generation. An additional ten minutes were provided for clarification regarding the study. Each participant was provided with the following materials prior to the study:

- A hard copy of presentation relevant to each set.
- Problem statement and list of requirements (single page)
- Sketch templates to draw concepts. The sketch template included sketching space and a text box to provide brief textual description of the concept. A sample sketch template is listed in the Appendix.

- The sketch templates were subtlety coded for recording the number of concepts generated per participant without revealing information regarding participant identity.
- The participants were informed that the sketches are coded to estimate the number of concepts generated per participant and would not reveal information related to identification of the participant. The coded templates also helped participants to modify previously generated concepts by mentioning the code of the previous concept sketch on the new template.
- Pencils and erasers as sketching accessories.

The participants were asked to limit one concept per page, annotate sketches and provide brief textual description of the concept. They were informed that the combination of sketch and textual description is essential for reviewers to analyze and understand the concepts. The procedure followed by each study set of Design Study II is listed in Table 4.1.

The participants of Set A were asked to follow the gallery method with timed sections for concept generation (see Figure 4.3). The participants were provided fifteen minutes to generate concepts individually without any explicit interaction or communication with other members of the group. This was followed by fifteen minutes of group discussion. During the group discussion, the participants were asked to display their sketches as in gallery method and explain the concepts to the other members of the group. The group discussion also allowed persistent questioning, negation, forward/ backward iteration steps, down-selection of ideas and uninhibited communication to

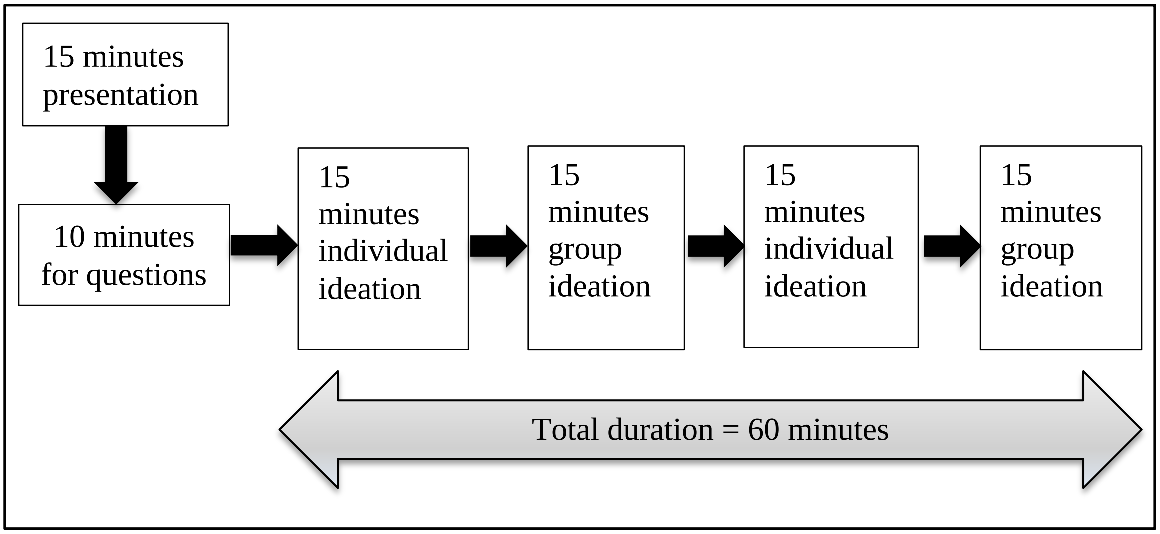

Figure 4.3: Treatment followed by Set A for Design Study II

generate widest possible solution concepts for the design problem as a group. This was followed by another fifteen minutes of individual ideation during which participants were allowed to either generate new concepts or modify previous concepts as per the feedback from group discussion. The participants were provided last fifteen minutes for group discussion to further develop and discuss their concepts and downselect best concept(s) they generated as solution(s) for the design problem.

The participants of Set B were asked to follow the gallery method with non-timed sections for concept generation (see Figure 4.4). The participants of set B were informed that they must follow alternate sections of individual ideation and group ideation for concept generation during the overall sixty minutes allotted to them. They were also informed that the time duration of each section was not significant as long as they adhered to the alternating the sections of individual ideation and group ideation for concept generation. Similar to Set A, the participants of Set B were asked to display the concepts like a gallery during the group ideation section. The participants were informed that group discussion also allowed persistent questioning, negation, forward/ backward iteration steps, down-selection of ideas and uninhibited communication to modify, eliminate and develop new concepts collectively as a group.

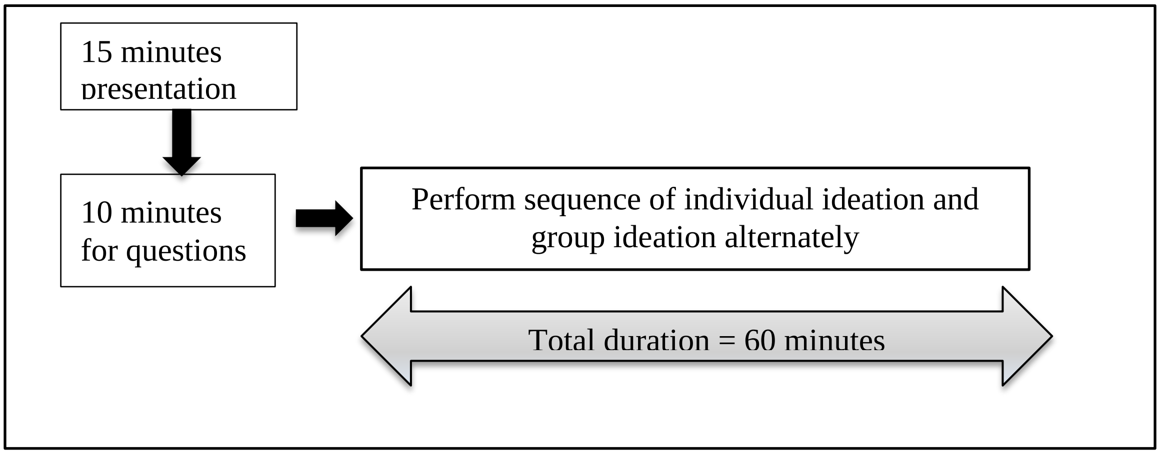

Figure 4.4: Treatment followed by Set B for Design Study II

The participants of set C were provided the experiment package and asked to generate as many concepts as possible in five days. This set was provided five days for concept generation to mitigate the effects of design fixation and also to analyze the effect of increased time duration on the quality of ideas generated by individual ideation. They were asked to submit the concepts in the same package at the end of the fifth day. The participants of this set were informed that usage of books, internet and other sources to seek solutions was not allowed because any such action could invalidate the study and results.

All the concept sketches were collected from the sets are evaluated. The weighted means (average quality) per requirement per set were evaluated using CATMOD function of SAS. The results also identified significantly different sets to determine the set (s) which generated highest average quality of concepts per requirement for the design problem.

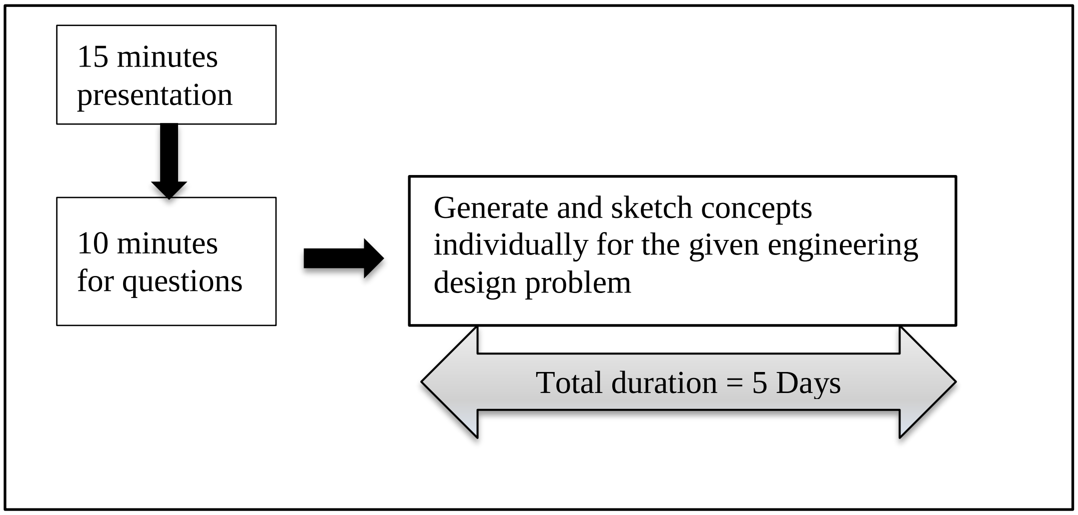

Figure 4.5: Treatment followed by Set C for Design study II

4.6 Analysis and Concept Evaluation

Similar to the Design Study I analysis, the sketches from this study were analyzed and graded by two raters independently. The concepts were first graded on a '0-1' scale (where '0' means absence of a particular requirement and '1' means presence of a requirement in the concept) followed by grading the sketches on a scale of 0-1-3-9. The concepts were graded on a scale of 0-1-3-9 to determine how well a concept addressed the requirements of the design problem. The guidelines for concept evaluation are listed below:

- The design concept must meet at least one of the functional requirements to be evaluated otherwise it shall be graded a zero.
- If subparts of a mechanism are sketched separately on different sketch templates, they will be considered and graded as a single concept.

- Incomplete sketches or missing information inhibiting the concept's understanding will be graded as zero.

- All concepts generated per set were evaluated to avoid skewing of data due to participant or set superiority in terms of consistently generating high quality concepts.

Three concepts were eliminated after the 0-1 scale evaluation because they failed to address at least one functional requirement.

4.6.1 Inter-Rater Agreement Results

The inter-rater agreement and intra-rater agreement scores of the raters were obtained for concept evaluation reliability. One of the two raters in Design Study II also rated the concepts in Design Study I. The concepts were initially graded using the rubric scale described in Appendix B 1 using the absent, low, medium and high scale (0-1-3-9). The results from the first IRA calculation were low across all the requirements depicting fair to moderate agreement between the two raters. Hence the next step was to refine the rubric. The raters were repeatedly trained with sample sketches to reach consensus over the refined rubric. The refined rubric used for grading is described in Table 4.3. In the refined rubric, the description of scores 0-1-3-9 were modified for better understanding and clarification necessary for grading the concepts. An illustrative grading of concepts using the refined rubric is listed in Appendix B. The raters performed three iterations of concept evaluations and inter-rater agreement values were computed using the iterations (I1, I2, I3).

Table 4.3: Refined rubric for scale 0-1-3-9 used for Design Study II concept evaluation

Requirement	**0 (Absent)**	**1 (Low)**	**3 (Medium)**	**9 (High)**
R1: Accepting can (s)	Absence of mechanism to accept can (s) for crushing	Mechanism with unstable components to hold the can(s). Insufficient information on mechanism / components holding the can. Impossible to construct or install.	Adequate information on components of mechanism. Fairly possible to construct with minor changes, addition of new features or modifications.	Highly efficient mechanism with supporting information about components/ mechanism. Possible to construct, can completely work.
R2: Crushing can (s)	Absence of mechanism to crush accepted can (s)	Mechanism with unstable components to crush the can(s). Insufficient information on mechanism / components used to crush the can. Impossible to construct or install.	Adequate information on components of mechanism. Possible to construct with minor changes, addition of new features or modifications.	Highly efficient mechanism with supporting information about components / mechanism. Possible to construct. Doesn't require additional or supporting components.

Requirement	**0 (Absent)**	**1 (Low)**	**3 (Medium)**	**9 (High)**
R3: Height of crushed can is 15mm	No mechanism to ensure that can (s) are crushed	The mechanism crushes the can to a variable height / insufficient information to determine height of crushed can.	The mechanism consist of features to crush can(s) to height of 15mm ± 2mm. Mechanism fairly possible to construct with additional supporting components. Might need additional information on certain aspects of the mechanism.	The mechanism ensures that the height of crushed can is less than 15mm with the presence of explicit features. Possible to construct. Doesn't require additional or supporting components.
R4: Storage of can (s)	No mechanism to store crushed can (s)	Poor mechanism to store can(s), impossible to construct, unstable components. Insufficient information on components or mechanism.	Fairly possible to store can(s), Mechanism possible to construct with minor changes, addition of new features or modifications.	Highly efficient mechanism to store can(s), completely possible to construct, doesn't require modifications to components to perform functions.

Requirement	0 (Absent)	1 (Low)	3 (Medium)	9 (High)
R5: Ease of operation	No information about mode of operation	Highly difficult to operate due to complex features or very high manual strength required. Insufficient information to access the ease of operation.	Fairly possible to operate or requires some manual strength. Possible to construct with additional or supporting components.	Very easy to operate. Very low manual effort required, simple user interface for automated mechanism such as switch/knobs. Doesn't require additional or supporting components.
R6: Safety of operation	No mechanism to ensure safety of operation	Highly risky and unsafe to operate with high probability of personal injury. Insufficient information to access the safety of operation.	Fairly safe to operate. Needs additional supporting elements. No apparent personal injury can cause tiredness or exhaustion if instructions are not followed.	Highly safe to operate. Doesn't need additional or supporting elements.

Requirement	0 (Absent)	1 (Low)	3 (Medium)	9 (High)
R7: Portability	Portability not addressed, large heavy mechanisms /components	Very low portability. Large, heavy mechanism/components with some portability features like wheels. Difficult to handle due large size or complex structure or presence of heavy components. Insufficient information to access portability	Fairly compact mechanism with efficient portability features, some modifications required to make handling easy. Requires additional supporting components and detailing of certain aspects of the mechanism.	Highly portable such as a coffee machine. Compact in size, easy handling features. No modifications required to handle.
R8: Accessibility of crushed can (s)	No accessibility to crushed can(s)	Poor accessibility of the crushed cans/ insufficient information on components or mechanism. No features or means to access crushed can(s)	Fair accessibility means to the crushed can(s), needs additional or supporting components and detailing of certain aspects of mechanism.	Very easy accessibility means to the crushed can(s), doesn't require additional or supporting components.

The inter-rater agreement scores using the refined rubric are listed in Table 4.4. The inter-rater scores indicate increase in agreement between the raters (refer to Table 3.4) and therefore, no further changes were required to be made in the rubric. The scores from iteration – I3 were used as final scores for the concept evaluation. The intra-rater scores were computed using I2 and I3 and are listed in Table 4.5.

Table 4.4: Inter-rater agreement scores using refined rubric for concept evaluation

Iteration	Requirements							
	R1	*R2*	*R3*	*R4*	*R5*	*R6*	*R7*	*R8*
I1	0.45	0.40	0.42	0.32	0.35	0.40	0.42	0.47
I2	0.64	0.62	0.67	0.63	0.62	0.64	0.64	0.64
I3	0.66	0.67	0.64	0.68	0.60	0.64	0.64	0.64

Table 4.5: Intra-rater agreement scores for Design Study II concept evalaution

Rater	Requirements							
	R1	*R2*	*R3*	*R4*	*R5*	*R6*	*R7*	*R8*
R1	0.58	0.48	0.55	0.48	0.59	0.62	0.68	0.62
R2	0.62	0.63	0.69	0.68	0.74	0.62	0.65	0.69

4.6.2 Statistical Data Analysis

Similar to the Design Study I, in this study the weighted means (average quality) for each set were calculated using CATMOD function of SAS. The level of significance was kept at 10% due to the exploratory nature of the study, degree of control in design criteria and power of test-sample size [67]. The CATMOD function of SAS also identifies contrasting sets or significantly different sets. Similar to Design Study I, the significantly different (or contrasting set) user study sets were identified with p-value less than 0.10. Once the contrasting sets were identified, the average quality scores were compared to identify the set with highest average quality of concepts addressing the respective requirement. The significantly different user study sets for each requirement with the corresponding p-value are listed in Table 4.6. The statistically different sets per requirement identified by CATMOD evaluation and the set with higher average quality of concepts per requirement are listed in Table 4.7.

Table 4.6: Weighted means (average quality) of Design Study II concepts per set per requirement

Set	Total Concepts	Requirement							
		R 1	*R 2*	*R 3*	*R4*	*R5*	*R6*	*R7*	*R8*
A	22	2.22	2.18	1.00	2.32	1.5	3.45	1.86	0.50
B	9	2.75	3.00	1.75	5.25	4.00	4.25	3.50	0.38
C	7	1.57	1.42	0.86	1.42	1.00	0.42	1.00	0.00

4.7 <u>Results and Discussion</u>

The following results are based on the scores obtained from CATMOD analysis listed in Table 4.6and Table 4.7:

Table 4.7: Design Study II statistically significant set per requirement

Requirement	Contrasting sets	p-value	Statistically Significant Set Weighted mean
R1: Accepting can(s)	A vs. C	0.08	A =2.22
	B vs. C	0.02	B= 2.75
R2: Crushing can(s)	A vs. C	0.06	A= 2.18
	B vs. C	0.01	B=3.00
R3: Height of crushed can(s)-15mm	B vs. C	0.02	B=1.75
R4: Storage of can(s)	A vs. C	0.05	A=2.32
	A vs. B	0.05	B=5.25
	B vs. C	0	B=5.25
R5: Ease of operation	B vs. C	0.33	B=4.00
R6: Accessibility of crushed cans	A vs. C	0	A=3.45
	A vs. B	0	B=4.25
	B vs. C	0.01	B=4.25
R7: Operation Safety	A vs. B	0.05	B=3.50
	B vs. C	0	B=3.50
R8: Portability	none	none	none

For R1, Set A (gallery method with timed sections) and Set B (gallery method with non-timed sections) was identified as significantly different from Set C (individual ideation). The comparison of the average quality score for the sets indicated that Set A and Set B generated high average quality concepts than Set C for addressing the respective requirement. Similarly, the average quality of concepts generated by Set A and Set B is greater than Set C for addressing R2. For R3, the average quality of concepts generated by Set B was found to be higher than the average quality of concepts generated by Set C. The Set A and Set C were not identified as significantly different for R3 which implied that there was no difference in the average quality of concepts generated by the two sets for addressing this requirement. For R4, the average quality of concepts generated by Set A and Set B was greater than the average quality of concepts generated by Set C. Additionally, the average quality of concepts generated by Set B was found to be greater than the average quality of concepts generated by Set A. The average quality of concepts generated by Set B was greater than the average quality of concepts generated by Set C for addressing R5. The Set A and Set B were not identified to be significantly different. Additionally Sets A and C were also not identified as significantly different for this requirement. This indicated that there was no difference in the average quality of concepts generated by Set A and Set C, and Set A and Set B for this requirement. For R6, the average quality of concepts generated by Sets A and B was found to be greater than the average quality of concepts generated by Set C. The average quality of concepts generated by Set B was found to be greater than the average quality of concepts generated by Set A for this requirement. For R7, the average quality of concepts generated by Set B was greater than the average quality of concepts generated by Set C and Set A. There were significant sets identified for R8. This implied that there was no difference found in the average quality of concepts generated by the three sets for addressing R8. The average quality of concepts generated by gallery method with non-timed sections was found to be greater than average quality of concepts generated by individual ideation for addressing seven out of the eight requirements. The gallery method with timed sections generated significantly higher average quality of concepts than individual ideation for three out of the five functional requirements.

4.8 Summary

This section summarizes the conclusions on the Design Study II results.

The Set A (gallery method with timed sections) generated the maximum number concepts followed Set B (gallery method with non-timed sections). The Set C (individual ideation) generated the least number of concepts. The statistically significant sets were identified for each requirement except one non-functional requirement –portability. There were no statistically significant sets identified for addressing the non-functional requirement of portability. This indicates there is no difference in the average quality of design concepts generated by the three sets for addressing this requirement. The Set A and Set B produced greater average quality of concepts than Set C for addressing the functional requirements –accepting can(s), crushing can(s), storage of can(s) and the non-functional requirement- accessibility of crushed can(s). There is no difference in the average quality of concepts generated by Set A and Set B for the two functional requirements- accepting can(s) and crushing can(s). This indicates that for these two functional requirements, the timed and non-timed sections of the gallery method did not have any significant effect on the average quality of concepts. The average quality of concepts generated Set B were significantly greater than the average quality of concepts generated by Set A for addressing three requirements- storage of can(s), accessibility of crushed can(s) and operation safety. There was no difference in the average quality of concepts generated by Set A and Set C for addressing the requirements- operation safety, ease of operation and height of crushed can(s) - 15mm. The number of concepts generated through individual ideation during Design Study II was not found to be significantly different. The increased time period of five days in Design Study II to mitigate design fixation did not increase the quality of concepts generated by individual ideation.

Based on the results, the average quality of concepts generated by gallery method with timed sections was found to be higher than the average quality of concepts generated by individual ideation for addressing three functional requirements. The gallery method with non-timed sections generated highest average quality of concepts for five functional requirements and two non-functional requirements than individual ideation. The average quality of concepts generated by individual ideation was not found to be greater than the average quality of concepts generated by gallery method with timed sections or gallery method with non-timed sections for any of the requirements. **The results support the null hypothesis 1- RH2.1**. The results from Design Study II validate the results from Design Study I and support RH1. The average quality of concepts generated by Set A and

Set B were not identified to be significantly different for five requirement of the design problem. **The lack of sufficient evidence supports the null hypothesis 2- RH2.2 .**

Chapter Five
FACILITATED IDEATION WORKSHOP

5.1 Overview

The facilitated ideation workshop was designed and conducted in collaboration with ME 402 undergraduate students of Clemson University working on Capstone design project. The two design studies conducted for this research were controlled experiments with voluntary participation from students whose performance and decisions would not have direct consequence on their career. It is hard to evaluate whether the participants of the controlled experiments performed objectively due to the lack of incentives during the studies. The participants of the design studies that followed the gallery method for idea generation represented pseudo groups; where the participants developed concepts individually and as a group but lacked to exhibit true characteristics of group dynamics, working and collaborating in group (all members developed concepts individually but struggled to developing these concepts together as a group, combining two or more concepts to further develop an idea and down-selection of concepts as a group). The limitations of the design studies could be due to the nature of controlled experimentation. However, the ME 402 Capstone design project is a real-time industry sponsored project where members of a design team are required to function as a group towards a common goal and set of objectives. It provided a platform for undergraduate students to function as design engineers where their performance and decisions would have direct consequence on their career. It comprises of a real-world engineering design project with strict time-dependent objectives and deadlines

During the facilitated ideation workshop, three Capstone design teams were facilitated to generate concepts for a design project using the gallery method. The design teams were assisted by a facilitator to follow and utilize the gallery method for concept generation. Past research indicates that the limitations of group interaction during an ideation session can be limited and regulated with the help a facilitator [25, 36, 44]. The limitations of group ideation if not addressed can significantly affect the quality of ideation outcome [28]. During the facilitated hybrid ideation workshop, each design team met with the facilitator for a period of six weeks (minimum of sixty minutes/week) for concept generation. At the end of six weeks, a survey regarding the facilitated hybrid ideation workshop was obtained from design teams.

5.2 Objective

The objective of the facilitated hybrid ideation workshop is to conduct a preliminary investigation at the use of gallery method for concept generation in a real world engineering design project setup. The facilitated hybrid ideation workshop with ME 402 Capstone design project provides our research an opportunity to study, analyze and evaluate the application of the hybrid ideation to generate increased quality of ideas and improve team dynamics in an industry sponsored project. The qualitative analysis of survey data was used address the Research Question 3.

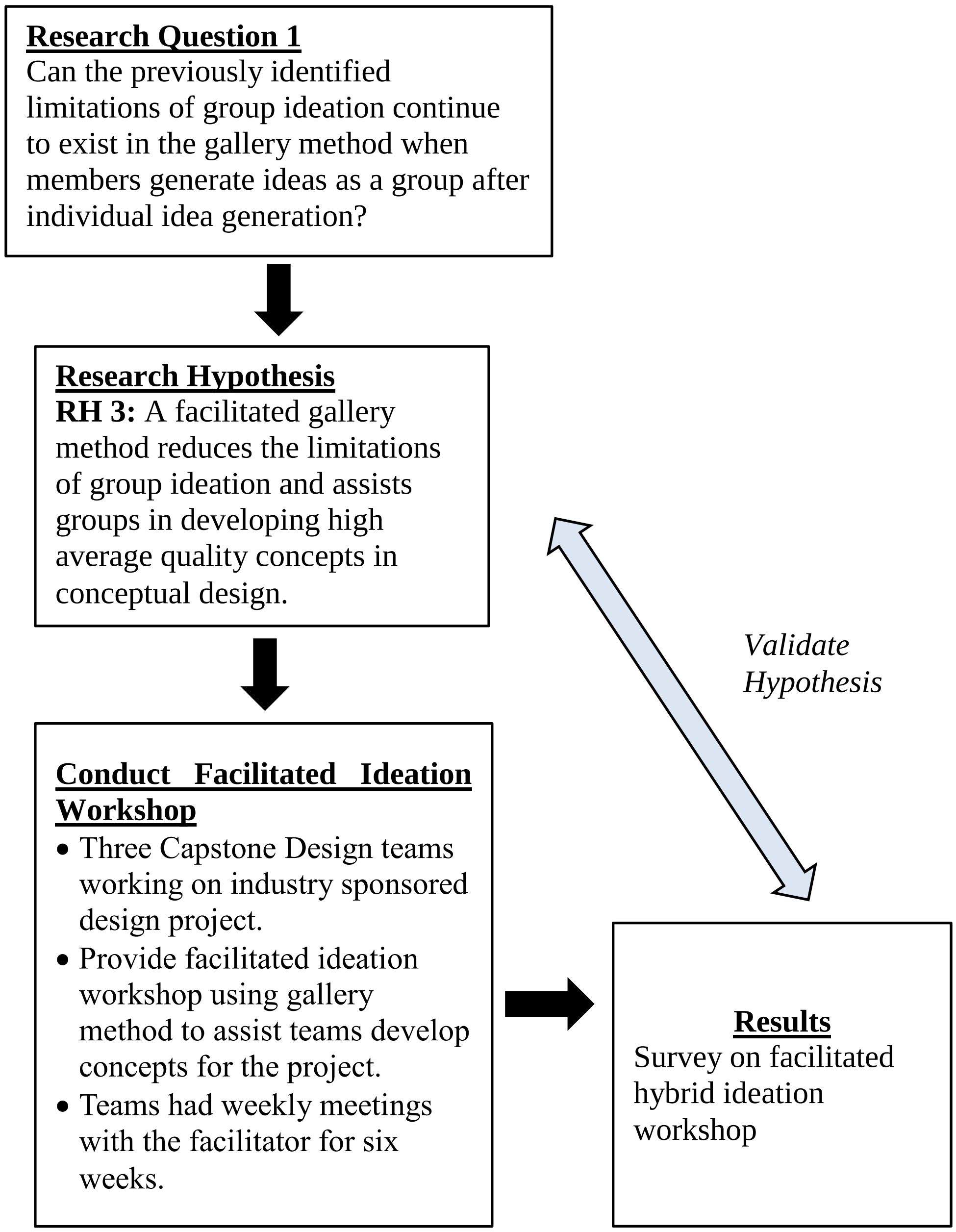

Figure 5.1: An overview of the Facilitated Ideation Workshop

5.3 Participants

- The participants of the facilitated ideation workshop constituted of 11 senior level mechanical engineering undergraduate level students of Clemson University.

- They were divided in to three teams with two teams comprising of 4 members each (Team A and Team C) and one team with 3 members (Team B).
- The participation in the facilitated hybrid ideation workshop was voluntary; the participants were informed that they could withdraw from the workshop anytime they felt that the outcome of the workshop was not useful or productive.
- The teams were also allowed to request for extended times per workshop session and increase the number of workshops per week.
- The facilitator was a mechanical engineering graduate level student with background in idea generation techniques and concept generation process.

5.4 Facilitated Ideation Workshop Procedure

The ME 402 capstone design project teams received the engineering design problem for the project from an industry sponsor. The teams were given two weeks to understand the design problem, formulate list of questions that needs to be addressed prior to concept generation. An in-person interview with the industry sponsor(s) to clarify doubts, understanding requirements and expectations from the project was also arranged. Based on their understanding of the engineering design problem and interaction with sponsor(s), each team was asked to formulate a design problem statement, set of design constraints and criteria for the engineering design problem. The design problem statement, design constraints and design criteria were developed by each team and was submitted for approval to the ME 402 advisory committee and industry sponsor. Once these were approved, the teams were ready to begin with concept generation. The teams were given six weeks for concept generation.

The design teams were asked to register online for a sixty minutes of facilitated ideation workshop per week to aid the process of concept generation. The schedule for the workshop was electronically sent to the teams to sign up for the workshop. The teams were informed that based on their experience from the first facilitated ideation workshop, they can register for more than one facilitated hybrid ideation workshop per week and for increased time per workshop can also be arranged if required. During the first workshop, the facilitator explained that the teams would follow the gallery method for concept generation. Additionally a fifteen minutes presentation on concept generation, gallery method and results from prior design studies supporting hybrid ideation were provided prior to the commencement of the ideation session. The presentation also explained the objective of the workshop, expectations from students and duration of workshop. An additional ten minutes were provided for clarifications. The facilitator employed some ground rules to follow during the workshop to keep the team members focused on objectives, enhance the ideation process and to ensure participation from all the team members of a team [48]. The ground rules followed during the facilitated ideation workshop are stated as follows:

- Be respectful of each other.
- It is okay to disagree with an idea but not the person.
- Have no fear of saying anything- all are equal.
- No gossip.
- Try not to take anything personally.
- Don’t be possessive of your own idea.

- Let go of old ideas and be open considering new ones.
- Encourage discussions about ideas.
- Be present, ready to discuss topics, readings etc.
- Always sketch concepts and provide brief textual description of the concept.

The above listed ground rules were established due to the following reasons:

- It is essential that designers working in team settings perform objectively towards the project goals keeping aside judgments influenced by their emotions or personal prejudice. The idea generation phase of engineering design process must emphasize on the keeping aside judgments based on emotions or prejudice because these can hinder productivity of the process and the team as well [40], [48]. The presence of an external expert- the 'facilitator' ensures that members of a team are respectful to each other without letting emotions and prejudice affect their judgments and performance. The members must be reminded to not let any negative judgment regarding their idea(s) affect their interaction with the fellow team members during an ideation session [26].
- The facilitator must remind the team members during an ideation process that it is acceptable to express disagreement with an idea based on an objective evaluation with necessary technical evidence or reasoning to support their evaluation. The facilitator advises the team members to understand that any recommendation or suggestions towards improving an idea or rejecting a bad idea must be taken with a positive attitude. The facilitator encourages members to welcome objective

critique of their ideas further group discussions for continuous improvement of the team [18, 20, 21, 42, 43].

- For engineering designers, it is very important to think out of the box and be open to new ideas. The rule to disregard an idea because it is 'new' and 'unheard of' must be renounced [66]. It is stressed by the facilitator to the team members to disregard any fear of judgment by others while expressing their ideas. The fear of being judged by fellow team members can considerably decrease an individual's performance, confidence and interest in the project. The team members, therefore, should set aside prejudice or preexisting notions about fellow team members during the facilitated hybrid ideation workshop [18, 20, 21, 42-44].
- The team must set goals for each ideation session prior to the meeting. This enables members to prepare themselves, research and learn more about similar things which would initiate the subconscious or conscious thinking process where ideas can bloom when least expected [1, 63]. The facilitator can help team members list their thoughts or ideas and encourage them bring forward those ideas for discussion during the ideation session. For a design team to stay productive and meet objectives on time, it must focus on problems and avoid digressing from agendas. The team members must be reminded to not utilize time during an ideation process to gossip and neither squander time or resources on matters unrelated to the project [3, 6, 63].

For the first two weeks out of the six, each design team met with the facilitator atleast once a week for idea generation. Based on the progress and objectives met per week, the design teams met with the facilitator more than once in a week. The role of the facilitator during the ideation workshop was to ensure that each member of a design team participates in the idea generation workshop; receives the equal number of opportunities to share their thoughts without interruptions and limit over-riding from other members. The facilitator assisted teams to focus on objectives and workshop meeting agendas which were set prior to each workshop. The team members were required to prepare beforehand for each workshop meeting to increase productivity. The facilitator did not provide the students with any direct technical assistance related to the problem statement or feasibility of ideas generated or any direct ideas. The design decisions were made by the team as a group without any involvement of the facilitator. However, the resources such as textbooks, research papers, feedback on presentations and reports was provided by the facilitator to the teams for improving the performance of the design teams. The facilitator encouraged members of a team to consider combining ideas that can result into a new concept together, developing on each other's ideas and objective critical analysis to determine feasibility and non-feasibility of generated ideas. The facilitator also assisted team members to divide work responsibilities ensuring that all members were given tasks to limit the occurrence of free-riding and social loafing. A typical session of the facilitated hybrid ideation workshop comprised of the following (See Figure 5.2):

The gallery method employed by the facilitator during the workshop was similar to the design studies. At first, the individual members of a team were asked to generate ideas followed by group discussion as a team. During the group discussion, the members were asked to explain their concepts to the team and provide a sketch or drawing to assist better understanding of the concept. At the end of the presentation of concepts, the facilitator asks members to enlist advantages and disadvantages of each concept presented. This process was repeated until all team members presented their ideas. Based on the list of requirements, constraints and criteria generated by the team, the facilitator asked the members to rate all the concepts presented on a scale with highest number of the scale equivalent to the best idea and lowest number of the scale to the worst idea. The scale was chosen depending on the number of ideas presented during the workshop meeting. For instance, if a total of 6 ideas were presented by the team for a 'design area of potential', the members were required to rate these ideas on a scale of 1-2-3-4-5-6 with 6 being the best idea and 1 being the worst idea. This was done to downselect the best or good concept(s) from the total number of concepts generated. The approach of generating wide number of ideas followed by down-selection to choose the best concept(s) is referred to as a convergent-divergent strategy in idea generation. This strategy of convergent –divergent tasks has been used in past research to increase team productivity with ideation [45]. After the ranking the ideas, the members were asked to announce the rank for each idea presented. The ranks are noted on a board by the facilitator and the top three ideas for each category or area of design are chosen. The reason for selecting three ideas is with the consideration that there is a possibility that some of the selected ideas might be eliminated in the later ideation rounds when ideas for the entire mechanism (including all the design areas of potential) will be combined.

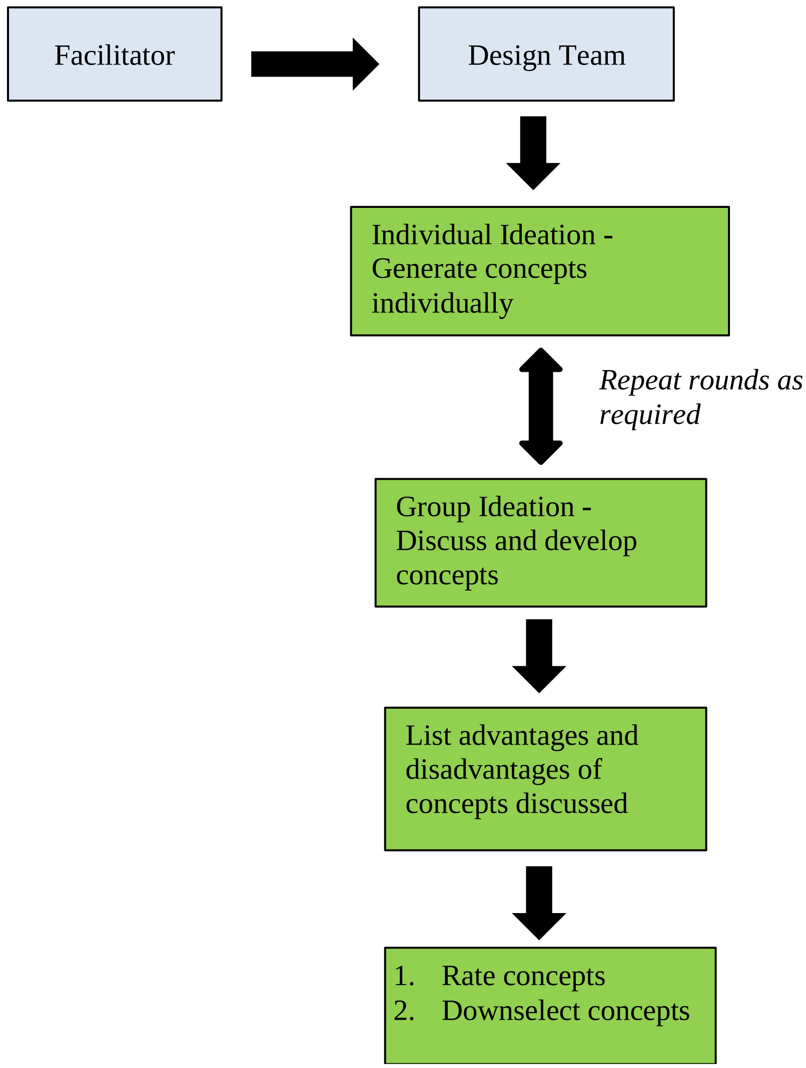

Figure 5.2:A workflow of activities performed during the Facilitated Ideation Workshop

At the end of the workshop, the objectives for following workshop meeting were formalized. The facilitator ensured each team member took responsibility for the work to be done. Each team was required to provide a weekly presentation on progress made in terms of developing concepts for the design problem. The facilitator also assisted teams on the presentation by providing feedback, resources and division of workload. This routine was carried out for six weeks. The end of the sixth week marked the completion of conceptual design phase of the project. At the end of the conceptual design phase, the teams were required to deliver a presentation of their final design concept(s) to the industry sponsors. At the completion of the facilitated ideation workshop, the students were required to provide feedback on the facilitated hybrid ideation workshop through a survey. The results for this section are based on the survey. The survey questions and responses are listed in Appendix C. The following section discusses the results from the survey and performance assessment scores.

5.5 Results

The following results are obtained through the evaluation of the facilitated ideation workshop survey and performance assessments. The survey responses and assessment scores are listed in Appendix C.

1. All the participants of the three ME 402 Capstone design team had experience working in a design team project in the past. Fifty percent of them worked on ME 401 projects and the rest on other projects. Ninety percent of these teams had four team members per project.
2. Sixty seven percent of the participants had a good overall experience while working during the design team project in past and the remaining thirty three percent had a bad experience because they did not follow any particular technique to develop ideas, distribute work responsibilities amongst team members and due to the lack of responsibility in certain team members.
3. Forty eight percent of the participants did not follow any technique to generate ideas in the past project whereas the remaining participants utilized design

techniques and tools such as brainstorming, functional decomposition, and morphological chart to generate ideas. Amongst these techniques, it was found that functional decomposition and morphological chart were the most commonly used techniques.

4. For the ME 402 Capstone design project, the team members of each team know each other mostly as friends or classmates and nearly seventy percent of them have known each other for over a year. Ninety percent of the participants have experience working with their current team members on other team projects in the past.
5. Sixty percent of the participants claimed having worked with some of the current team members in the past has enhanced their performance in the ME 402 Capstone design project in terms of expression of ideas and division of responsibilities.
6. Eighty two percent of the participants expressed that the facilitated ideation workshop is an effective way to generate design ideas for ME 402 Capstone design project.
7. Seventy three percent of the participants built or iterated on each other ideas during the facilitated ideation workshop. Sixty four percent of these participants expressed that building or iterating on each other's ideas was effective for generating design ideas for the current project, increased their creativity and also challenged their creativity as individuals to generate unique ideas for the team.

8. Sixty percent of the participants expressed that an individual to group approach during the facilitated ideation workshop was effective for generating ideas and increasing the overall quality of ideas generated.
9. Eighty two percent of the participants declared that the facilitated ideation workshop improved their team performance to collectively function better as a team and generate increased quality of ideas.
10. Seventy three percent of the participants agreed that the times provided for facilitated ideation workshops were flexible.
11. The following features of the facilitated ideation workshops helped the teams the most to generate design ideas:
    a. Following an individual to group approach for ideation and discussion of ideas.
    b. Formulating objectives for next meeting and presentation.
    c. Feedback on weekly ME 402 presentation.
    d. Flexible timings of the facilitated hybrid ideation workshop.
    e. Assisting groups to focus on project objectives and help meet the objectives on time.

The all three design teams showed development and progress in generating conceptual ideas for the design project over the six weeks of facilitated hybrid ideation workshop.

5.6 <u>Conclusions</u>

The facilitated hybrid ideation workshop using the gallery method was effective for the design teams of ME 402 Capstone Design project for generating high quality of concepts during conceptual design. Based on the results, the presence of the facilitator improved team dynamics, increased performance of the team members and the teams as well. The teams supported the use of facilitated gallery method for concept generation, to increase the productivity of the team, individual members and the quality of concepts during Capstone projects. This is an agreement with the results of the two design studies. The facilitated ideation workshop provides initial results and support for the application of the gallery method in real design projects such as Capstone projects.

Based on the feedback in the survey from the participants, the teams encouraged conducting facilitated hybrid ideation workshop for future ME 402 Capstone design projects. **RH3 is supported to be true.**

Chapter Six
RESEARCH SUMMARY AND FUTURE WORK

This chapter outlines how tasks addressed the research objective and research questions. A summary of the results obtained future work to be done to further build on this research are also provided.

6.1 Addressing Research Questions

The research tasks were conducted to address three questions. The results obtained with respect to addressing the research questions are listed in this section and in Table 6.1.

6.1.1 Research Question 1:

Can the gallery method be more effective than individual ideation for generating high quality concepts for engineering design problems?

The gallery method combines features of individual ideation and group ideation for concept generation [1, 2, 4, 9, 44]. The results from the design studies provide evidence to suggesting that hybrid ideation generates higher average quality of concepts than individual ideation. In the past, studies have argued that individual ideation is more effective than group ideation [8, 10, 19, 23, 28, 29, 24, 30-32]. Additionally, limitations of group ideation have also been identified by past research [4, 7, 15, 22, 24, 30–32]. However, group ideation is still commonly practiced in industrial settings. To resolve the existing conflict, this research proposed to use a technique that would combine the benefits of both individual and group ideation that can allows members of a group to first generate ideas individually followed by developing them further as a group. This is achieved through the gallery method that leverages the productivity of individual members and the group to collectively generate high average quality of concepts.

Based on the results from the design studies, the average quality of concepts generated by the gallery method was found to be greater than the average quality of concepts generated by individual ideation. In both design studies conducted in this research, the gallery method was found to generate high average quality of concepts than individual ideation for addressing the functional requirements. In Design Study II, the gallery method generated higher average quality of concepts for addressing both functional and non-functional requirements compared to individual ideation. The effectiveness of gallery method to generated high average quality of concepts for engineering design problems was tested in the design studies. The results support that the gallery method generates high quality concepts than individual ideation for engineering design problems. Thus, Research Question 1 is addressed.

6.1.2 Research Question 2:

Do the timed sections of individual ideation and group ideation in the gallery method affect the quality of concepts generated?

The gallery method comprises of alternating sections of individual ideation and group ideation. In the individual ideation section, individuals of a group generate and sketch concepts silently. This is followed by group ideation where the members discuss and review the previously generated concepts as a group. In the group ideation, the members are allowed to discuss the concepts, combine two or more concepts to generate new concept(s) and list advantages and disadvantages of each concept to downselect concepts as a group. This is followed by another round of individual ideation and group ideation. This alternating sequence of individual ideation and group ideation is a characteristic feature of the gallery method. This sequence can be repeated as many times as required until the goal of idea generation is achieved. However, there is lack of evidence to determine the effect of the timing each section of this sequence on the average quality of concepts. An exploratory investigation regarding the effect of time duration of sections in the gallery method on the average quality of concepts was conducted in Design Study II. In the study, two variations of the gallery method – gallery method with timed sections and gallery method with non-timed sections were compared. It was found that the gallery method with non-timed sections generated higher quality of concepts than the gallery method with timed sections for three non-functional requirements out of a total of eight requirements (less than 50% of total requirements). The results from this study are insufficient to validate the effect of time duration on the sections of the gallery method to increase concept quality. The results from Design Study II support Research Hypothesis 2. See Table 6.1.

6.1.3 Research Question 3:

Can the previously identified limitations of group ideation continue to exist in the gallery method when members generate ideas as a group after individual idea generation?

To address the research question 3, a facilitated ideation workshop following the gallery method was conducted with three Capstone Design teams. The true characteristics of group were not observed during the design studies. The participants followed the instructions of the experiment to generate concepts using the gallery method but it was found that they did not work well as a group during the group ideation phase. The individuals developed concepts on their own but lacked the motive to develop, modify or downselect concepts as a group. This observation was made during both design studies. This behavior could be caused by the following factors:

1. The absence of incentives.
2. The lack of necessity to function as a group.
3. No direct consequence of their decisions or performance on individual career.

Therefore, the facilitated ideation workshop was conducted with design teams working on a real-time industry sponsored design project. Contrary to the design studies, it was mandatory for the participants of the facilitated ideation workshop to work and function as a design team with the results directly having a consequence on their academic results. This required the individual members of a team to find new ideas or identify improved ideas collectively as a group through discussion, negation and iteration.

The results from the design studies provide experimental evidence that the gallery method increases concept quality. Based on the results from the design study, the facilitated ideation workshop was conducted with real design teams to validate the results under a non-experimental setup. The nature of this investigation was qualitative. A survey was conducted to obtain feedback on the workshop. Based on the qualitative analysis of the survey data, the research concluded that the facilitated ideation workshop assisted teams to develop high quality concepts and improved their performance as a team to achieve the objectives of the project. Thus Research Question 3 is addressed.

Table 6.1: Answers to Research Questions

Research Questions	Research Conclusions
RQ 1: Can the gallery method be more effective than individual ideation for generating high quality concepts for engineering design problems?	The average quality of concepts generated by gallery method is greater than average quality of concepts generated by individual ideation.
RQ 2: Do the timed sections of individual ideation and group ideation of the gallery method affect the quality of concepts generated?	The average quality of concepts generated by gallery method with both timed and non-timed sections are not greater than average quality of concepts generated by individual ideation. The average quality of concepts generated by gallery method with timed sections and gallery method with non-timed sections are not statistically different.
RQ 3: Can the previously identified limitations of group ideation continue to exist in the gallery method when members generate ideas as a group after individual ideation?	A facilitated ideation workshop with the gallery method helped teams develop high quality of concepts and improved the productivity of design teams.

6.2 Future Work

The following are few research opportunities that have been identified to validate and support the effectiveness of the gallery method to increase idea quality in conceptual design for engineering design problems.

- One of the major setbacks of this research is the small sample size of the design studies. As mentioned in the previous sections, due to constraints of time, participant availability and cost, the design studies were conducted using a small sample size. The absence of sufficient sample size also limited further exploration of the Research Question 2. Future studies are recommended with large sample size to strengthen and validate the results from this research to support the practice and application of the gallery method to increase idea quality for engineering design applications.

- The results from Design Study I indicated no significant difference in the quality of concepts generated to address the non-functional requirements. In Design Study II, the concepts generated by the gallery method with timed sections were found to be statistically significant for three functional requirements and one non-functional requirement; less than 50% of the total requirements. Therefore, the quality of concepts to address the non-functional requirements in the design studies was not found to be significant. This indicates that it is difficult to generate high quality of concepts to address the non-functional requirements in the early concept development phase. This observation needs to be validated through future studies. *RQ: During the early concept development phase, how can the gallery method increase the average quality of concepts to address the non-functional requirements?*
- *RQ: How will conducting the design studies with different users modify the results obtained in this research?* Another opportunity to validate the research conclusions is to conduct the design studies and workshop with different users. Future research can be conducted with novice designers such as freshmen who have no prior experience in concept generation techniques and process, and

compare the results with experienced designers who have prior background of idea generation techniques and concept generation. Such an inquiry can help test the gallery method across different types of users. Such studies can also focus on capturing the increase in the quality of concepts over time while using the gallery method with different users.

- The research can be expanded in future by comparing the average quality of ideas generated by different group ideation techniques with average quality of ideas generated by individual ideation. It was beyond the scope of this research to compare all group ideation techniques with individual ideation. The group ideation techniques such as brainsketching, C-sketch, nominal technique can be compared with individual ideation with respect to generating high quality of concepts in conceptual phase for engineering design problems. The gallery method can also be tested against other group ideation techniques such as C-sketch, brainsketching and nominal technique to determine a best suited ide generation technique for developing high quality of concepts in engineering design. *RQ: How will the average quality of concepts vary when using group ideation techniques such C-sketch, nominal technique and brainsketching during concept generation?*
- In the Design Study II, the total duration of time provided for the individual ideation was five days. However, the actual amount of time spent by each participant for idea generation was not captured. *RQ: How will the time dedicated for concept generation in individual ideation of Design Study II be captured?* This

can be addressed in future by asking the participants to spend a fixed amount of time each day for concept generation.

- Also, further investigation needs to be done to compare the average quality of ideas developed by gallery method with timed sections and gallery method with non-timed sections. The overall gallery method is always time constrained [1, 2, 9, 44]. However, the effect of timing the individual ideation and group ideation sections of gallery method is an open research opportunity. *RQ: How will increase or decrease in time for individual ideation and group ideation of the gallery method affect the quality of ideas generated?* The Design Study II of this research can be expanded in future by exploring the effect of time durations in alternating sections of the gallery method.
- The facilitated ideation workshop conducted in this research was an initial attempt at applying the facilitated gallery method in real engineering design projects. The qualitative survey results only provide preliminary evidence regarding the usefulness of facilitated gallery method to increase group productivity and idea quality. *RQ: How will the results of this research vary by conducting quantitative analysis of the concepts developed by Capstone design teams of the facilitated ideation workshop?* This can be achieved by conducting quantitative analysis of final concept(s) developed by the design teams. Another opportunity to validate the effectiveness of facilitated gallery method would be to compare quality of concepts generated by controlled groups with nominal groups. The controlled groups will follow the facilitated gallery method and nominal groups will include

design teams without the facilitated gallery method. This research opportunity can be explored through future Capstone projects.

- As stated earlier, the use of voluntary participants for design studies could have an effect on the final results because the factors of voluntary participation and motivation can cause bias in the results. However, investigating the bias caused due to these factors was beyond the scope of this research. *RQ How will the results from this study vary if the design studies were performed as an in-class activity as opposed to voluntary participation? How does nature of participation (compulsory vs. voluntary) affect the effectiveness of an idea generation process?*
- Based on the results from the facilitated ideation workshop, 50% of the participants responded that they were friends with each other at the time of the project. 50% of the participants also responded that 'being friends' mildly enhanced their performance during the project. This increase in familiarity between team members and performance enhancement can result in good group dynamics in a design team. A design team with good group dynamics can benefit from a facilitated ideation workshop however, future research must be conducted with teams comprising of members who are not acquainted with each other. *RQ: How will the facilitated gallery method affect the average quality of ideas developed by design teams comprised of members who are not acquainted with each other?* This can be addressed by conducting the facilitated ideation workshop using the gallery method with such teams to evaluate its effect on concept quality and addressing limitations of group dynamics.

APPENDICES

Appendix A: Design Study I

A.1.: Rubric of scale 0-1-3-9 used for initial concept evaluation in Design Study I

Requirement	**Absent (0)**	**Low (1)**	**Medium(3)**	**High (9)**
Full Horizontal movement (F1)	No mechanism present	Bad mechanism, impossible to construct/ install, unstable components	Fairly possible mechanism, not very efficient, requires additional support components	Highly efficient mechanism, can completely work.
Full Vertical movement (F2)	No mechanism present	Bad mechanism, impossible to construct/ install, unstable components	Fairly possible mechanism, not very efficient, requires additional support components	Highly efficient mechanism, can completely work.
Locking the seat (F3)	No locking mechanism	Bad mechanism, impossible to construct locking mechanism.	Locking Mechanism present to lock & secure at positions.	Detailed & specific mechanism to lock and secure at all possible positions. Can work completely.
Noise under normal operating conditions (NF1)	Requirement not addressed.	Very high rattling of components or high noise due to moving components	Moderate rattling of components due to movement of components	Negligible rattling

Requirement	Absent (0)	Low (1)	Medium(3)	High (9)
Ease to move seat in horizontal direction (NF2)	Requirement not addressed.	Complex, difficult to operate and requires high manual strength. Difficult handling features	Medium manual effort - Pulling the seat manually. Needs more information on mechanism or needs additional components.	Simple and easy to operate with minimal effort- switch or knob like features present.
Ease to move the seat in vertical direction (NF3)	Requirement not addressed.	Complex, difficult to operate and requires high manual strength. Difficult handling	Medium manual effort - Pulling the seat manually needs more information on mechanism or additional components.	Simple and easy to operate with minimal effort- switch or knob like features present.

A.2.: Design Study I Illustrative Concept Evaluation

To understand how the design concepts were graded using the 0-1-9 scale, the grading for two design concepts are explained in this section. Example 1 (See Figure 6.1) is a design concept from Set 1 and Example 2 (See Figure 6.2) is a design concept from the Set 3. The grades for both design concepts per requirement are explained as follows:

Example 1

The sketch in Figure 6.1exhibits a seat mechanism with the seat mounted on a worm gear powered with a motor. The provision for seat to move horizontally is provided but there is lack of information for seat's vertical motion. The motor and moving worm gear contributes to increased noise during operating conditions. The mechanism is electronically operated with minimum effort required.

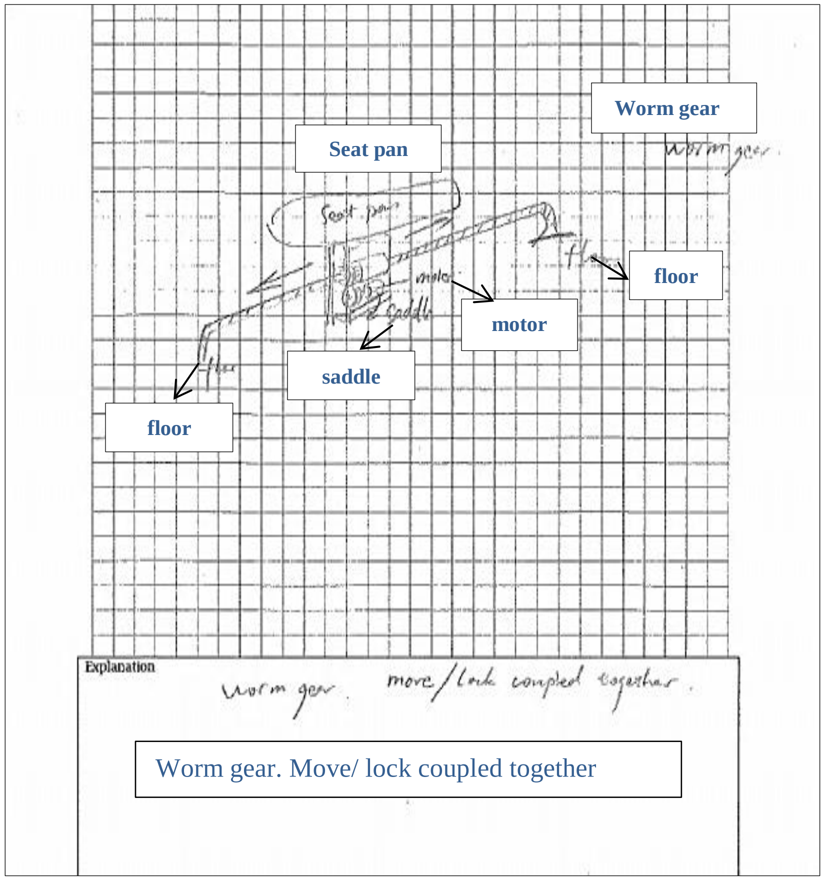

Figure 6.1: Example 1- Concept sketch from Set 1 of Design Study I

- *Full horizontal motion*- The seat is mounted on a worm gear powered by a motor. This facilitates the horizontal motion of the seat mechanism. The mechanism is graded 9 for addressing this functional requirement.
- *Full vertical motion*- There is no information regarding the vertical motion of the seat. There is no textual description provided in the text box addressing the requirement. The concept was graded a 0.
- *Locking the seat*- The worm gear is self-locking and therefore, the concept was graded a 9.

- *Noise under normal operating conditions*- The presence of motor can cause considerable noise during operation. The mechanism was graded a 1 for addressing the requirement.
- *Ease to move the seat in horizontal direction*- There are no components specified for operating the seat in horizontal direction. There is no information provided in the text box regarding how to operate the seat in horizontal motion. The concept was graded a 1.
- *Ease to move the seat in vertical direction*- There are no components specified for operating the seat in vertical direction. There is no information provided in the text box regarding how to operate the seat in vertical motion. The concept was graded a 1.

Example 2

Figure 6.2 illustrates a design concept from the Set 3 and the grades assigned per requirement are explained as follows:

- *Full horizontal motion*- The horizontal motion of the seat mechanism is powered by an acme lead screw and ball nuts using a motor. The mechanism is graded 9 for addressing this functional requirement.
- *Full vertical motion*- the vertical motion is facilitated hybrid using pneumatic cylinders powered by vehicle's vacuum line. The concept was graded a 9 for addressing this requirement based on the rubric.

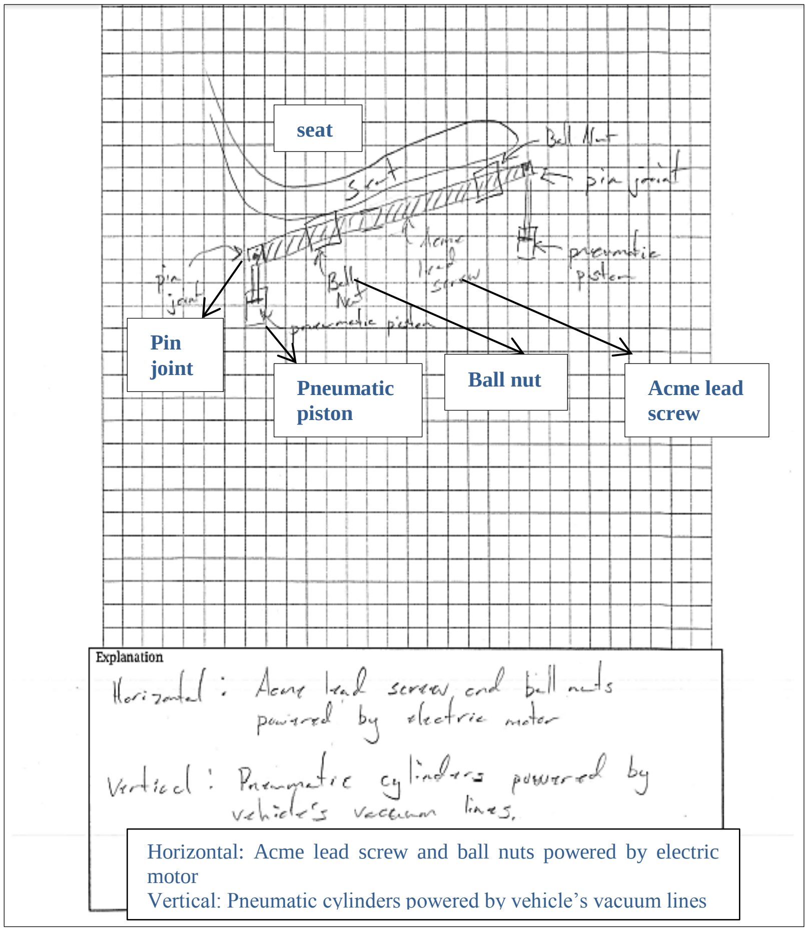

Figure 6.2: Example 2-Concept sketch from Set 3 of Design Study I

- *Locking the seat*- The presence of moving parts like lead screw and pneumatic piston cause very low noise during operation. The mechanism was graded a 9 for addressing the requirement.
- *Noise under normal operating conditions*- The presence of moving parts like lead screw and pneumatic piston can cause very low noise during operation. The mechanism was graded a 9 for addressing the requirement.
- *Ease to move the seat in horizontal direction*- There are no components specified for operating the seat in horizontal direction. There is no information provided in

the text box regarding how to operate the seat in horizontal motion. The concept was graded a 1.

- *Ease to move the seat in vertical direction*- There are no components specified for operating the seat in vertical direction. There is no information provided in the text box regarding how to operate the seat in vertical motion. The concept was graded a 1.

A.3: Concept Evaluation Scores for Design Study I Concepts

<table>
<tr><th>CODE</th><th>F1</th><th>F2</th><th>F3</th><th>NF1</th><th>NF2</th><th>NF3</th></tr>
<tr><td>I-1</td><td>9</td><td>0</td><td>9</td><td>1</td><td>9</td><td>1</td></tr>
<tr><td>I-2</td><td>0</td><td>9</td><td>9</td><td>9</td><td>0</td><td>9</td></tr>
<tr><td>I-3</td><td>9</td><td>9</td><td>9</td><td>1</td><td>1</td><td>9</td></tr>
<tr><td>II-1</td><td>9</td><td>9</td><td>9</td><td>1</td><td>9</td><td>9</td></tr>
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<tr><td>III-3</td><td>1</td><td>9</td><td>0</td><td>1</td><td>9</td><td>9</td></tr>
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<tr><td>IV-3</td></tr>
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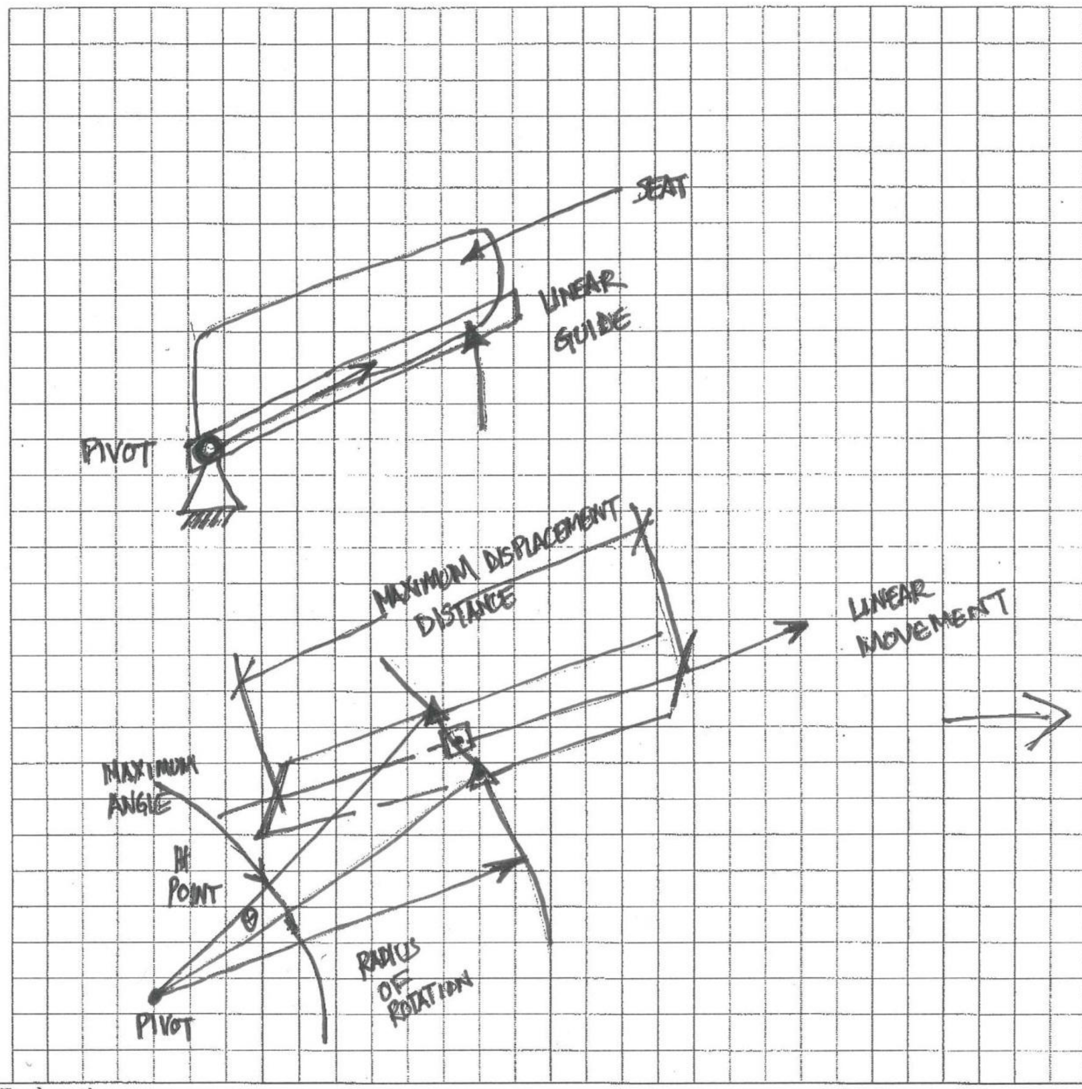
<tr><td>V-3</td></tr>
<tr><td>VI-1</td><td>1</td><td>1</td><td>0</td><td>1</td><td>9</td><td>9</td></tr>
<tr><td>VI-2</td><td>9</td><td>0</td><td>9</td><td>1</td><td>9</td><td>0</td></tr>
<tr><td>VI-3</td><td>1</td><td>1</td><td>0</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>VI-4</td><td>9</td><td>9</td><td>9</td><td>9</td><td>9</td><td>9</td></tr>
<tr><td>VI-5</td><td>1</td><td>1</td><td>0</td><td>1</td><td>9</td><td>9</td></tr>
<tr><td>VI-6</td><td>1</td><td>1</td><td>0</td><td>1</td><td>9</td><td>9</td></tr>
<tr><td>VI-7</td><td>1</td><td>0</td><td>0</td><td>1</td><td>9</td><td>0</td></tr>
<tr><td>VI-8</td><td>1</td><td>0</td><td>0</td><td>1</td><td>9</td><td>0</td></tr>
<tr><td>VI-10</td><td>1</td><td>0</td><td>0</td><td>1</td><td>9</td><td>0</td></tr>
</table>

CODE	F1	F2	F3	NF1	NF2	NF3
VIII-1	9	9	9	1	9	9
VIII-2	9	9	9	1	9	9
VIII-3	9	9	9	1	9	9
VIII-4	9	9	9	9	9	9
X-2	0	9	0	9	0	9
XI-1	0	1	9	1	0	9
XI-2	1	1	0	1	9	9
XI-3	1	1	0	1	9	9
XII-1	9	9	0	1	9	9
XII-2	9	9	9	1	9	9
XIV-1	9	1	0	1	9	9
XIV-2	9	0	0	1	9	0
XIV-3	1	1	0	1	9	9
XIV-4	1	9	0	1	9	9
XIV-5	1	1	0	1	9	9
XIV-6	9	9	0	1	9	9
XV-1	9	9	9	1	9	9
XV-2	9	9	9	9	9	9
XV-3	1	1	0	0	0	0
XV-4	9	9	9	1	9	9
XV-5	0	1	0	9	0	9
XV-6	1	1	0	9	9	9
XVI-3	0	1	0	1	0	9
XVI-4	0	1	0	9	9	9
XVIII-1	9	1	0	1	9	9
XVIII-2	9	1	0	1	9	9
XVIII-3	9	1	9	1	9	9
XIX-1	9	9	9	1	9	9
XIX-2	9	9	9	1	9	9
XIX-3	9	9	9	9	1	1
XIX-4	9	9	0	1	9	9
XX-1	9	9	0	1	9	9

A.4: Design Study I Concept Sketches

The following sketch concepts were collected at the end of Design Study I.



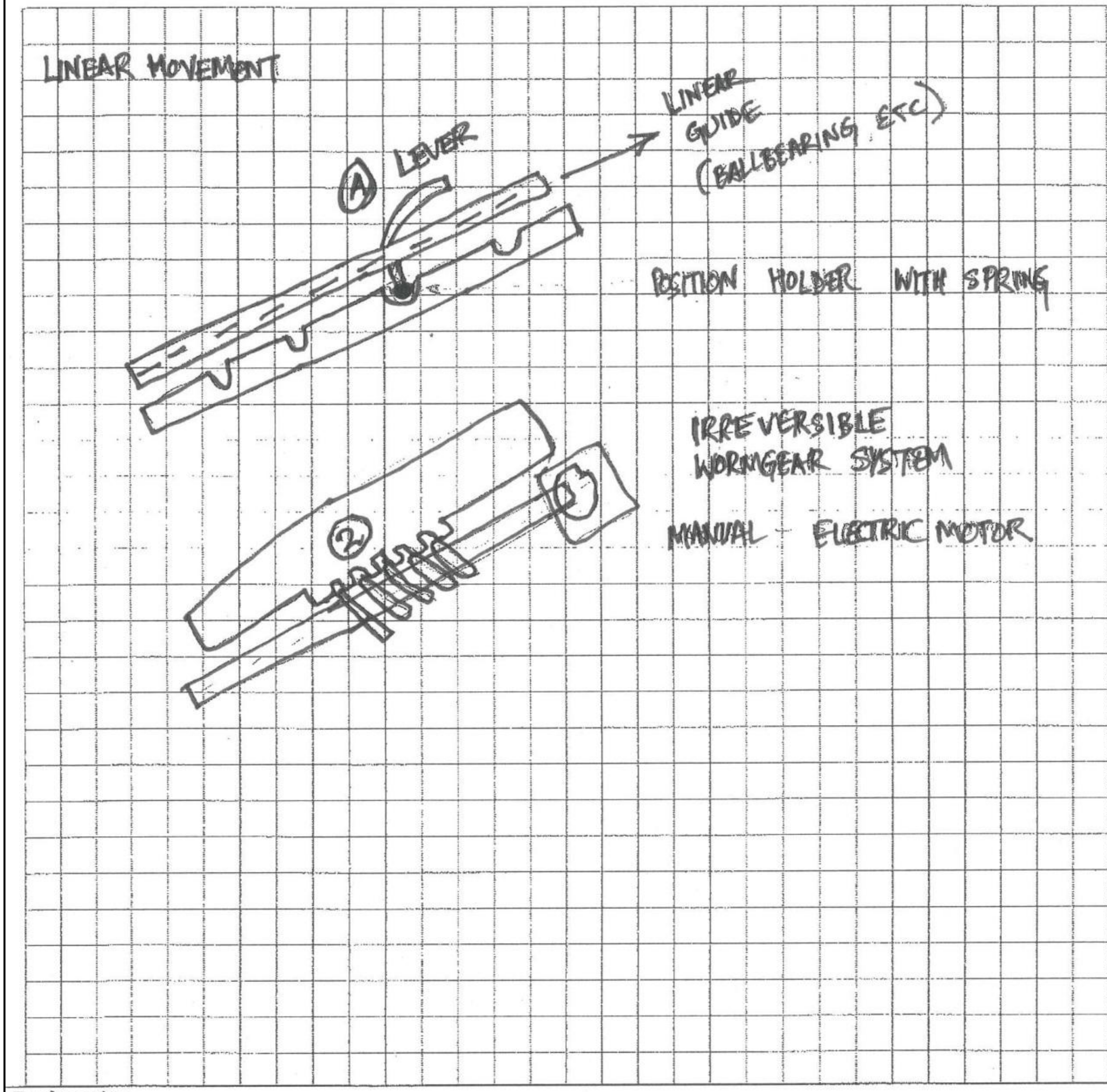
Explanation

① THE SEAT-PAN SHOULD MOVE AND ADJUST THE POSITION IN A LINEAR GUIDE.

② THE SEAT PAN AND THE GUIDE SHOULD ROTATE THE POSITION.

DECOUPLED SYSTEM

IV 1

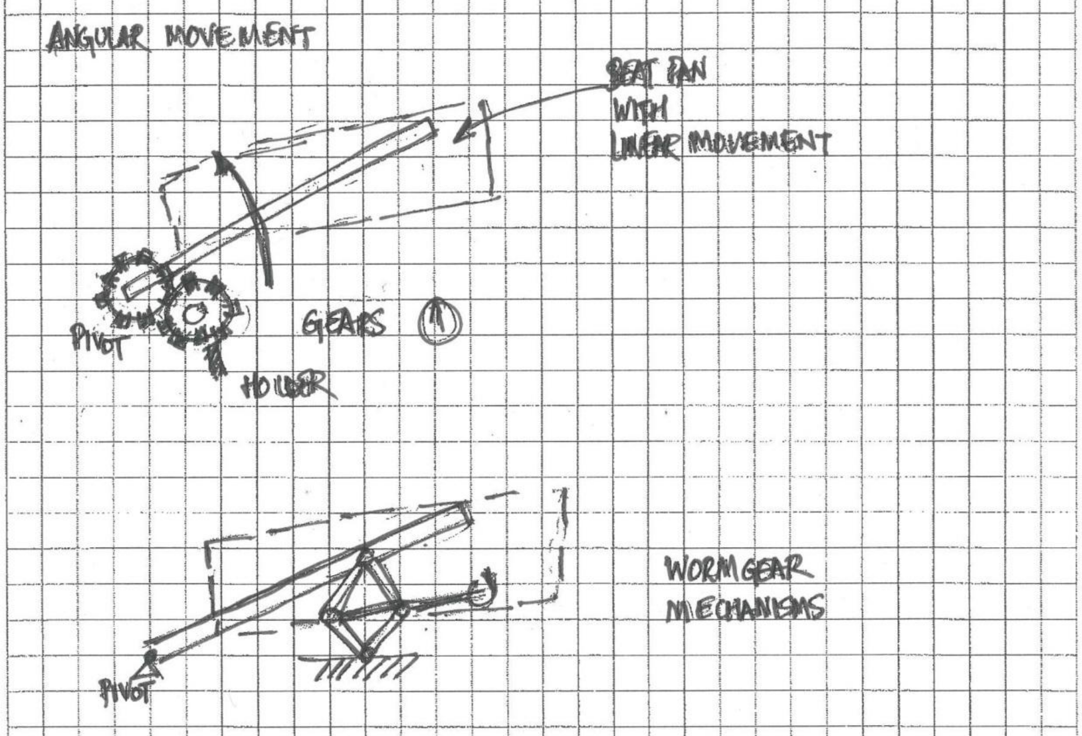


Explanation

IF THE SYSTEM IS DE COUPLE IN TWO MOVEMENTS WE CAN EACH MOVEMENT GENERATE SOLUTION

1. LEVER WITH SPRING TO DE ATACHED THE MECHANISM FROM THE HOLDER AND MOVE FRWD. FORCE MINIMUM BECAUSE LEVER AND SPRING HELP KEEP TIGHT IN HOLDER. AND HOLDER KEEP CONSTRAINT IN ALL DIRECTIONS
2. IRREVERSIBLE → ONLY TURNING WORM MOVES THE SEAT PAN. LOW FORCE. BUT A LOT OF MOVEMENT BUT NOT REQUIREMENT.
   ALLOWS ELECTRICAL MOTOR

IV 2

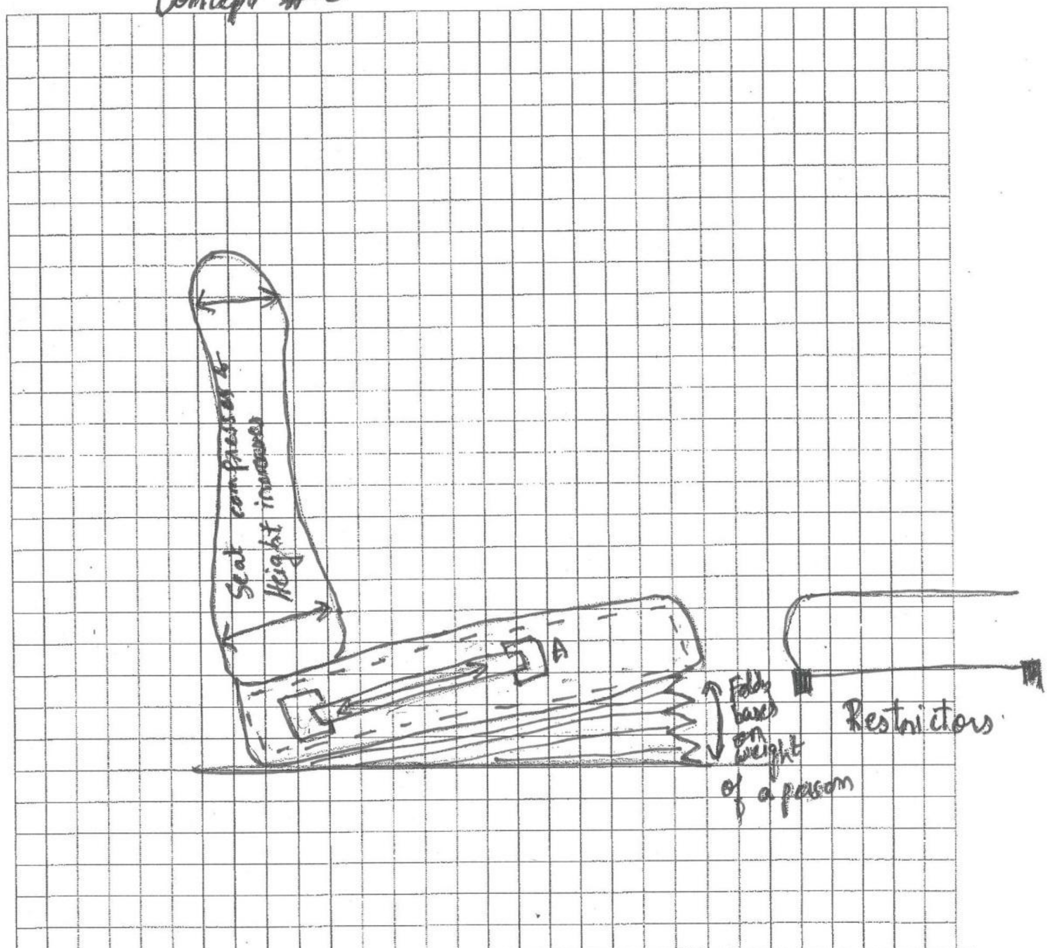


Explanation

① GEARS, GOOD FOR SMALL ROTATIONS. HOLDER MECHANISM TO DON'T LET GO BACK. USER SHOULD REALEASE HOLDER AND THEN GO FROM BEGINING. ALLOW ELECTRICAL MOTORS.

② IRREVERSIBLE WORMGEAR MECHANISM, LOW EFFORT, RELIABLE, NO DEFORM, RESISTANT. ALLOWS ELECTRICAL MOTOR.

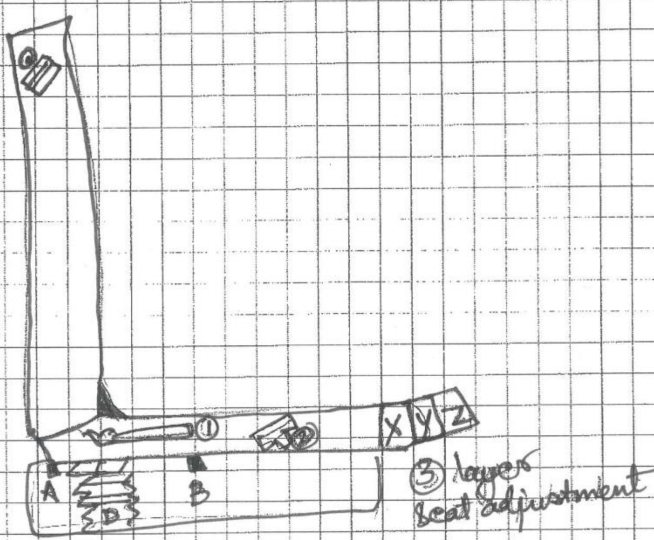
Concept #3



Explanation

A - Hydraulic forward movement controller - Avoids noise

Concept #2



Explanation

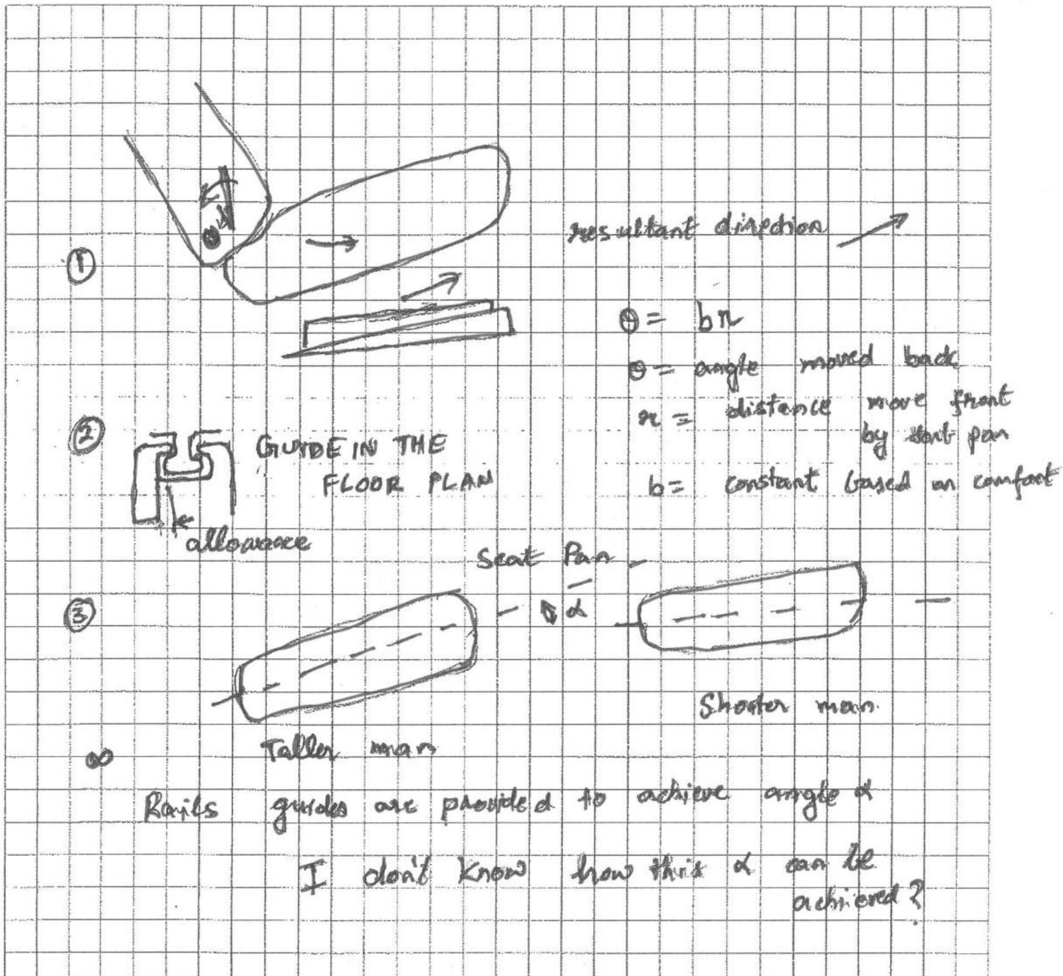
① Lower.

② A-B to restrict forward movement.

③ C-D Spring for up down

④ Seat buckle – Once buckled will send signal preventing > 20mm displacement

⑤ X-Y-Z the seat folds inwards based on height. ie For tall people the seat stratches till Z.. If a short guy sits, seat folds to X based on knee position.



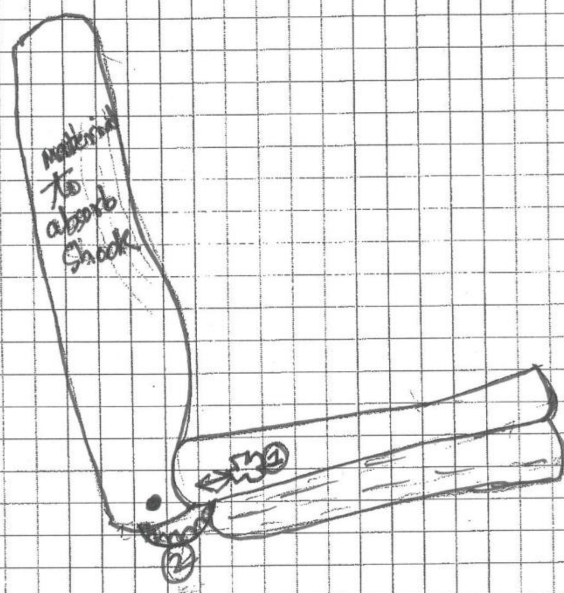
Explanation

① When the recliner moves back, seat pan will move forward over the guides provided over the Floor plan.

② Allowance in the guide should provide as a function to avoid noise. reduction (k) provide initial movement ≤20 mm

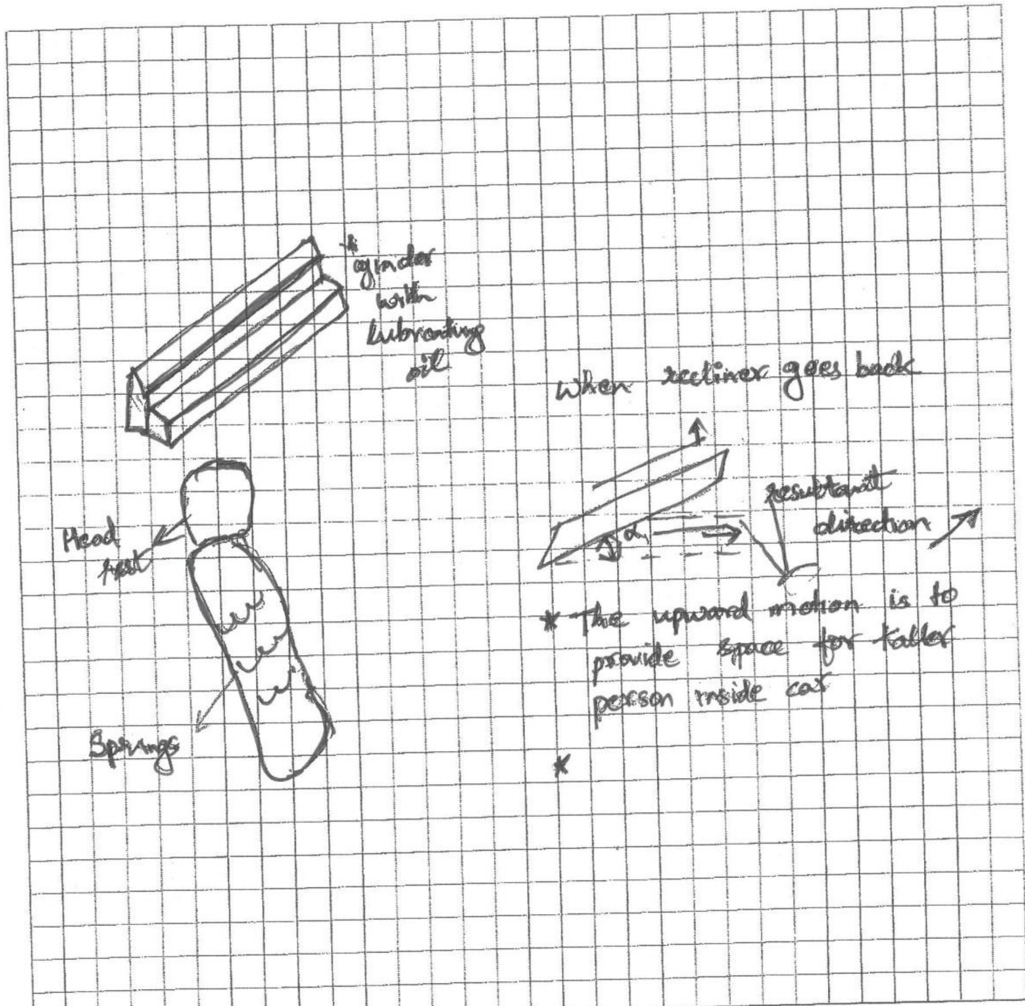
③ Angle α, will decide whether taller man or shorter man fits. α makes sure H-point windows moves to accomodate shorter or taller man.

Side View



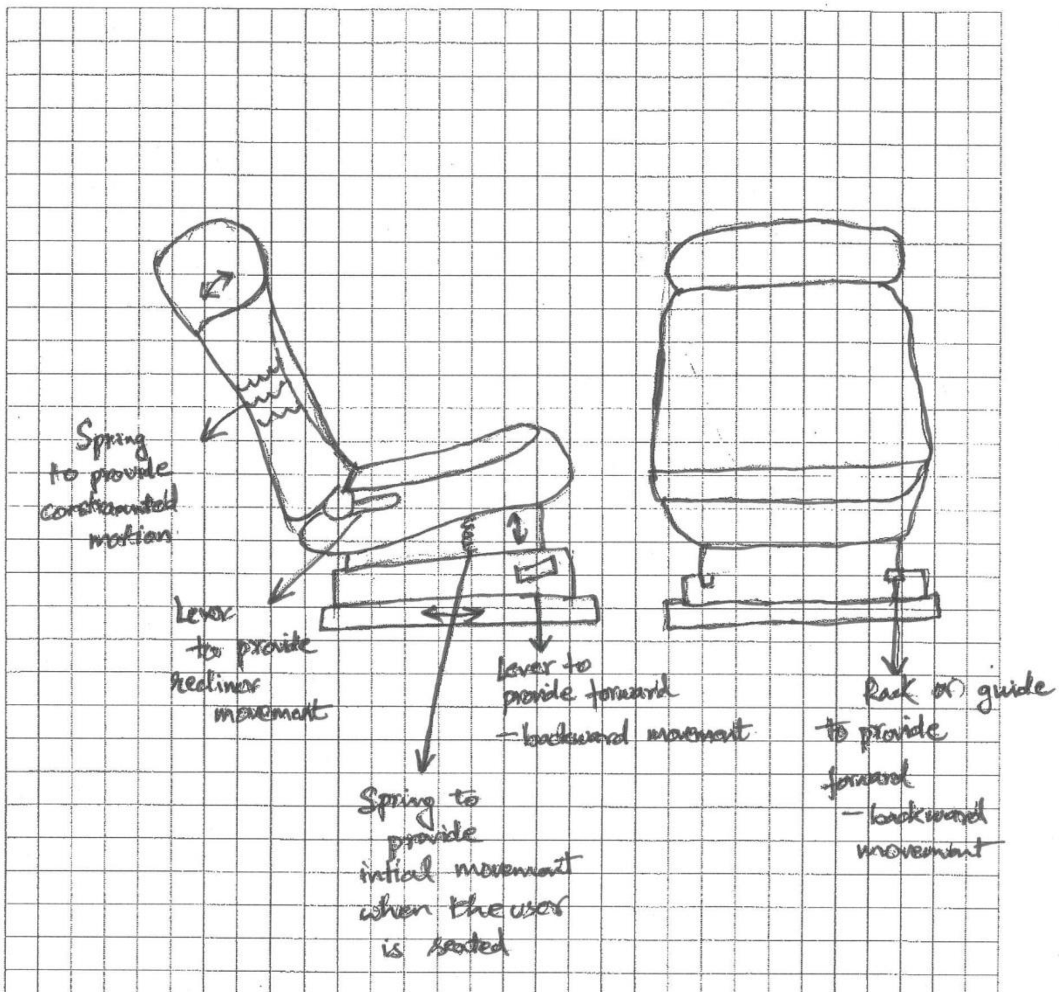
Explanation

① Seat adjustment (controller)
② gear mechanism to adjust angle.



Explanation

* Rail guides has to operate using hydraulic cylinders to provide movement at exact accuracy
* Guides should be lubricated to provide accurate friction & angle.
* Head rest would not have compressive springs, just fabric to provide rest

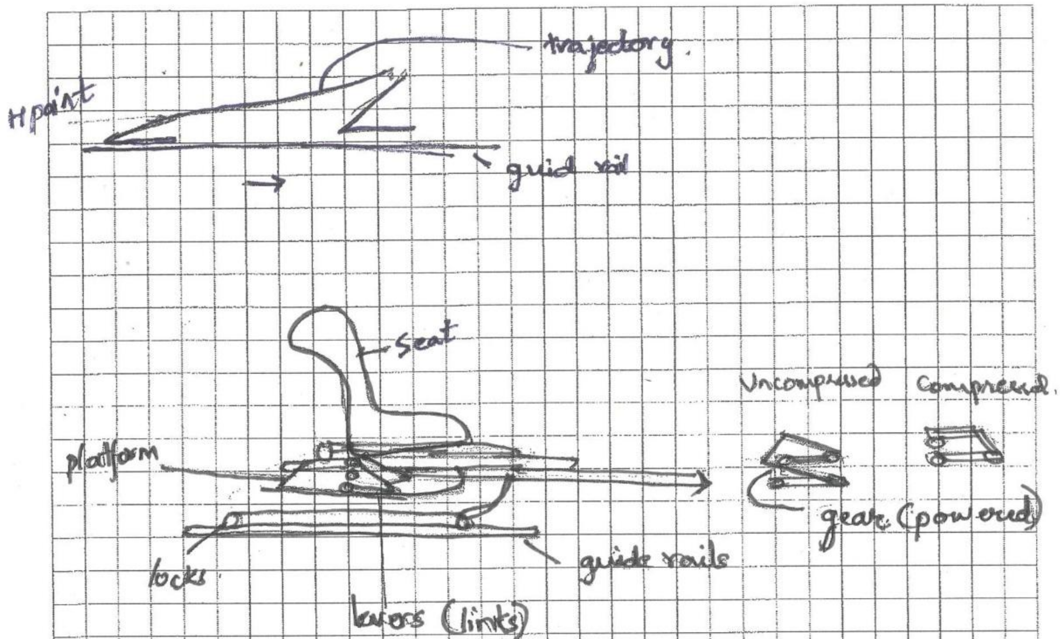


Explanation

* Spring towards the front of the seat, for provide initial movement to H-point window
* Separte Mechanical / Electronic controlled Levers are provided giving forward - backward movement and recliner movement
* Spring with Tension T such that recliner doesn't get deplaced more than 20 mm.

V

1

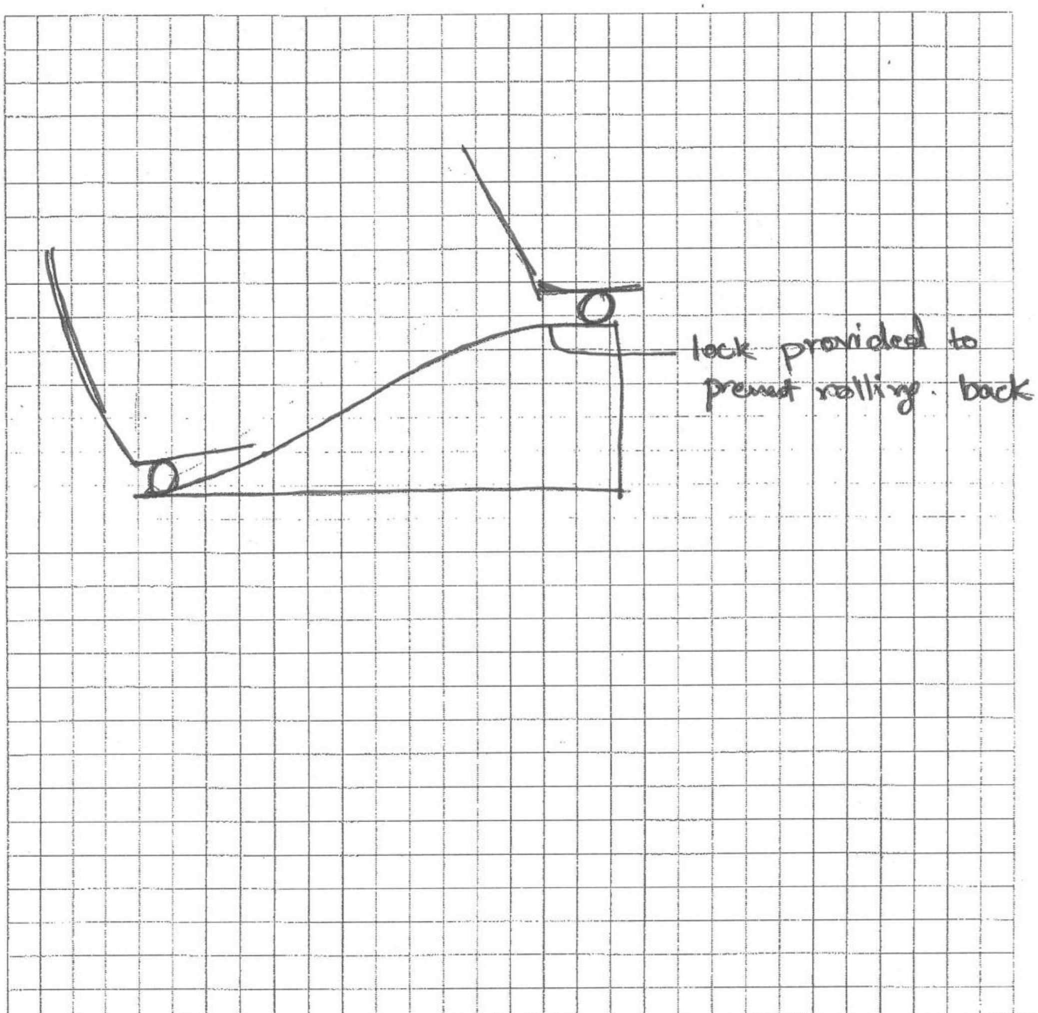


Explanation

A platform is able to move horizontally, with the help of guidrails. The platform has a set of levers, operated by a ~~Motor~~ power driven gears that can lift and lower the top half.

The seat is attached to the levers (links.)

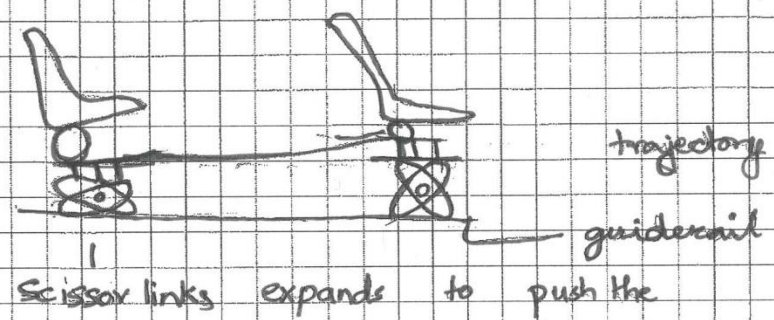
The movement on the platform and levers are connected



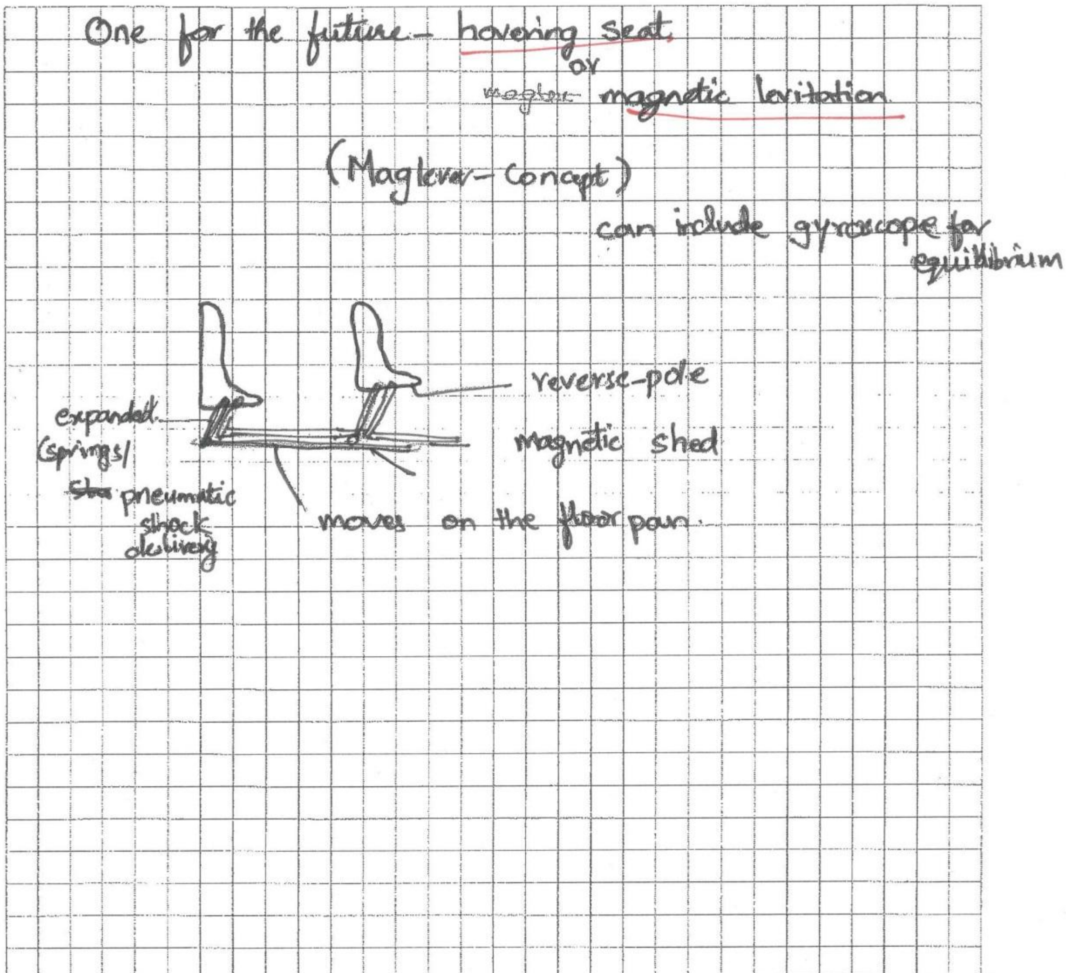
Explanation

The seat is powered to travel up and down the inclined

Lock are provided to prevent rolling back.



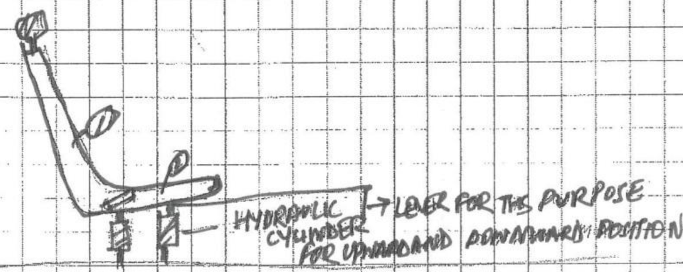
Explanation



Explanation

III

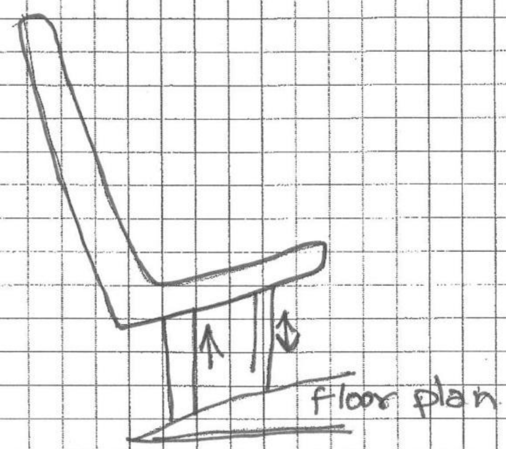
4



Explanation

I guess to achieve the 20mm we need to figure out a way such that when seat ① is reclined seat ② is programmed to move to distance 20mm I am not able to think of quick mechanism in the allotted time.

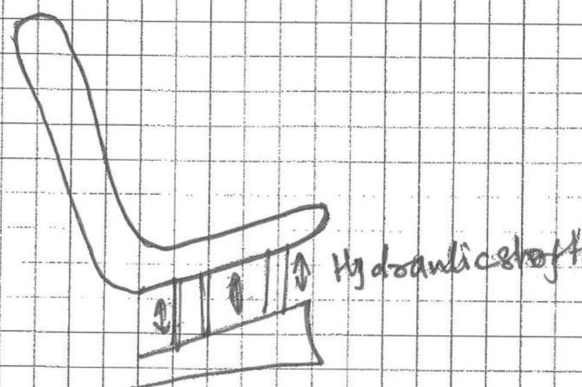
X 2



Explanation

The main frame should be held to the floor pan from the seat pan i-e only the recliner can be adjusted there holdings should be moved up & down

Cushioning should be there to menat rattle.

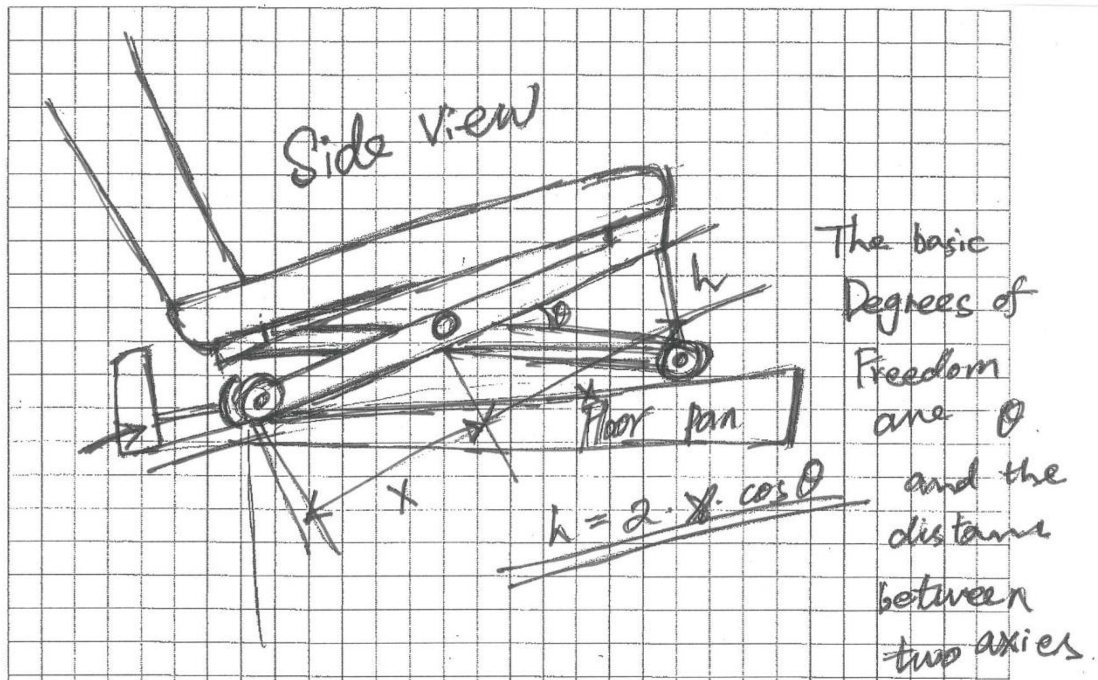


Explanation

Mechanism for movement: Electromechanical
Push of a button sends signals to move point A
as illustrated left or right with the help of pulley
North south movement can be facilitated by
hydraulic shafts which connect the lower end
of the seat plan to the floor pan
Deformity will not occur if properly grounded

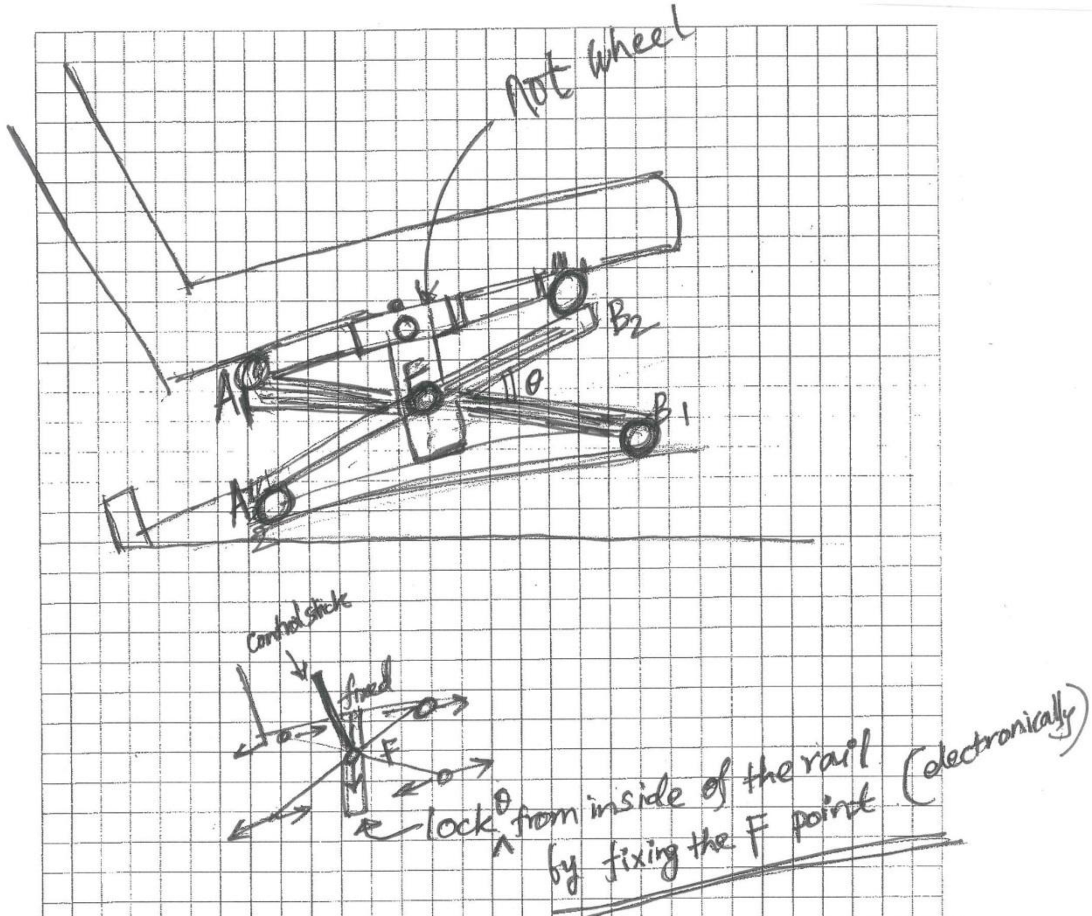
XVI

4



Explanation

By

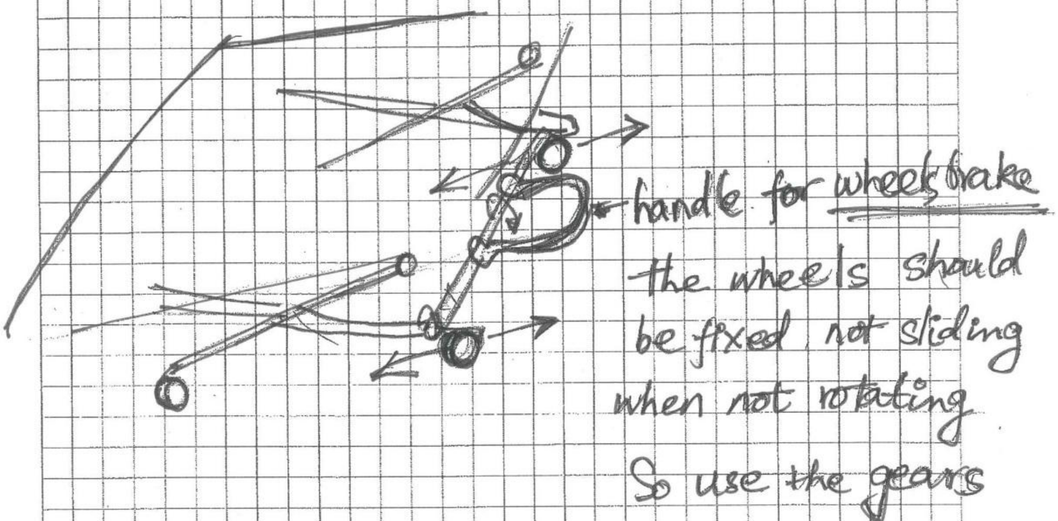


Explanation

To make the seat keep in a fixed angle against horizon. The point F should be in the middle of the both shelves A_1B_1 and A_2B_2 so $A_1B_2 \parallel A_2B_1$. We need wheels on both floor plan and the bottme of the seat (first design is wrong for this, be cause A_1B_2 has a changing distance, C should be fixed on the chair and F is moved along a rail fixed under the chair at C.

By moving A_2B_1, the chair can moved forward and back.

By changing θ, the chair canbe moved up and down.

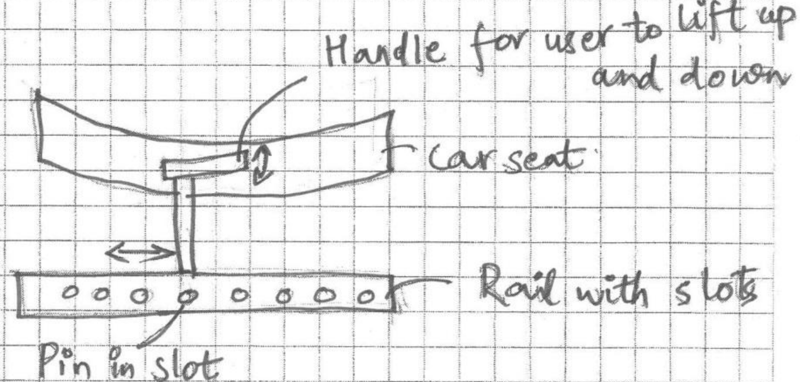


Explanation

XVIII

3

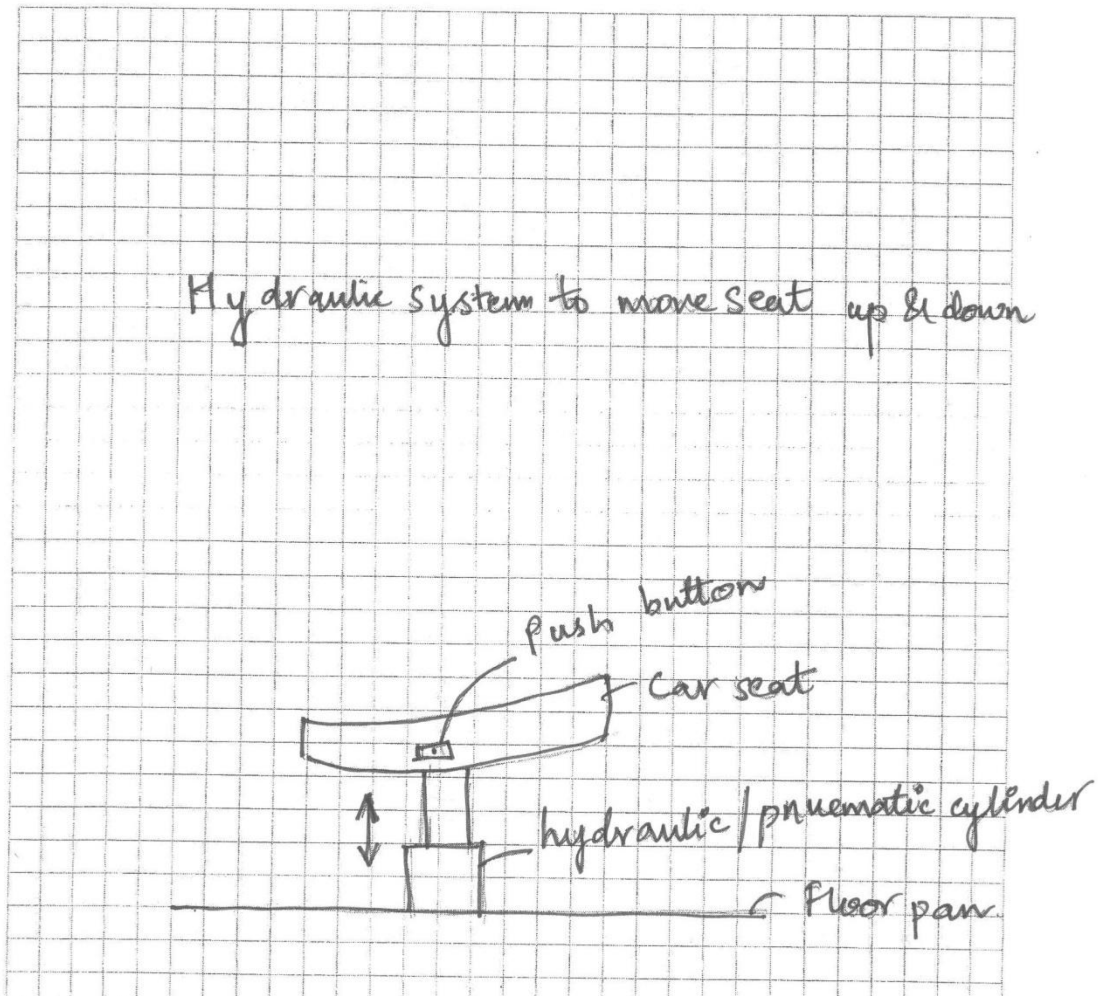
Pin in slot seat adjustor



Explanation As the user lifts the handle, pin at the other end, disengages from slot, which allows user to slide the seat back and forth. Once desired movement is achieved, the user can let go off the handle which engages pin in slot and locks seat in place.

I

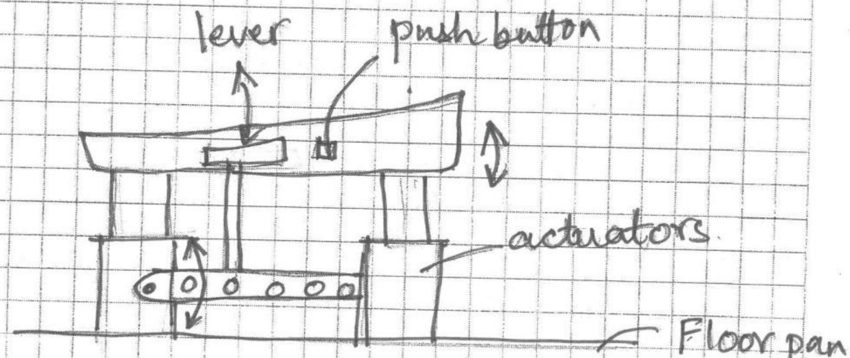
1



Explanation This is a more automated concept. As the user pushes button, it actuates hydraulic or pneumatic cylinder which allows user to move seat up and down as desired.

1 2

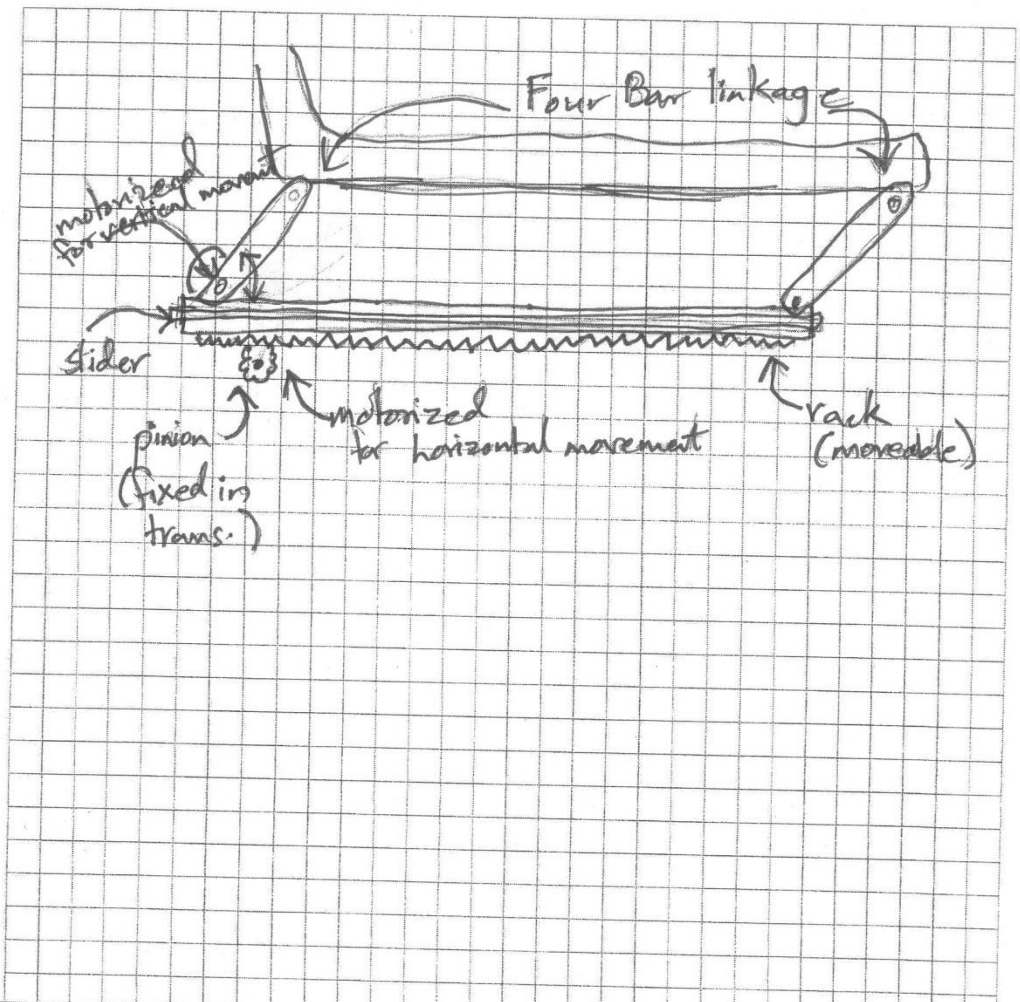
Cheap + simple



Explanation This is a combination of previous two ideas where the user can use the push button to actuate cylinders and adjust vertical movement, The slotted bar is pivoted so can move up & down The user can use the lever to adjust position of pin in slot to adjust front and back movement

1

4 3.



Explanation

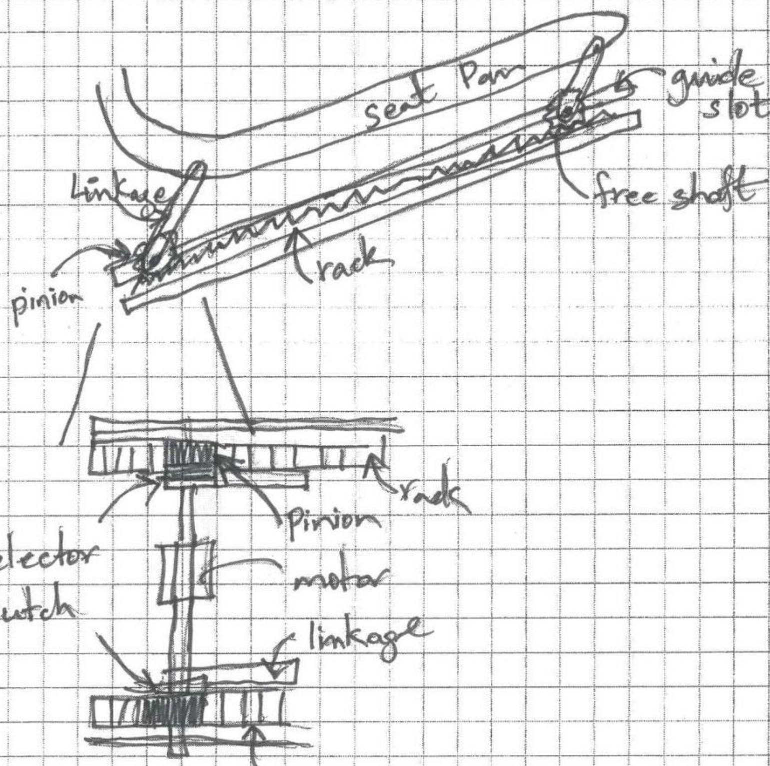
Translation on the largest dimension is achieved through a rack & pinion system.

Vertical translation is achieved by motorizing a joint in a 4-bar linkage system.

XIX

1

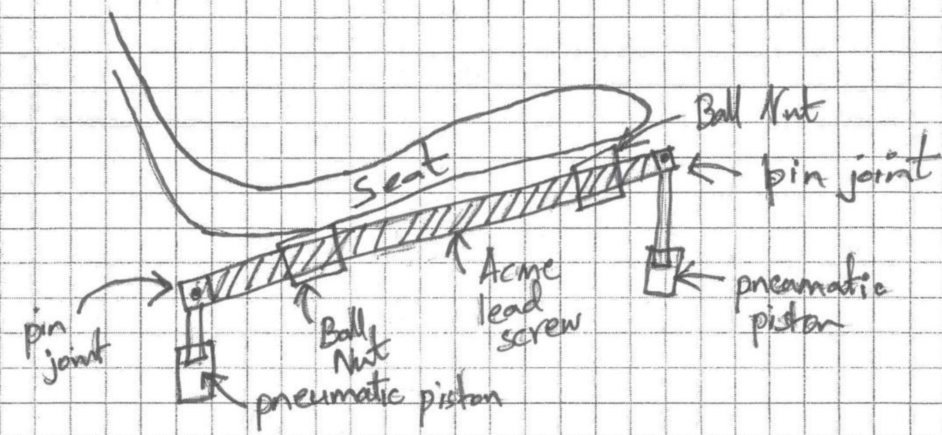
Most Practical



Explanation

pinions climb the rack for horizontal motion.

Li

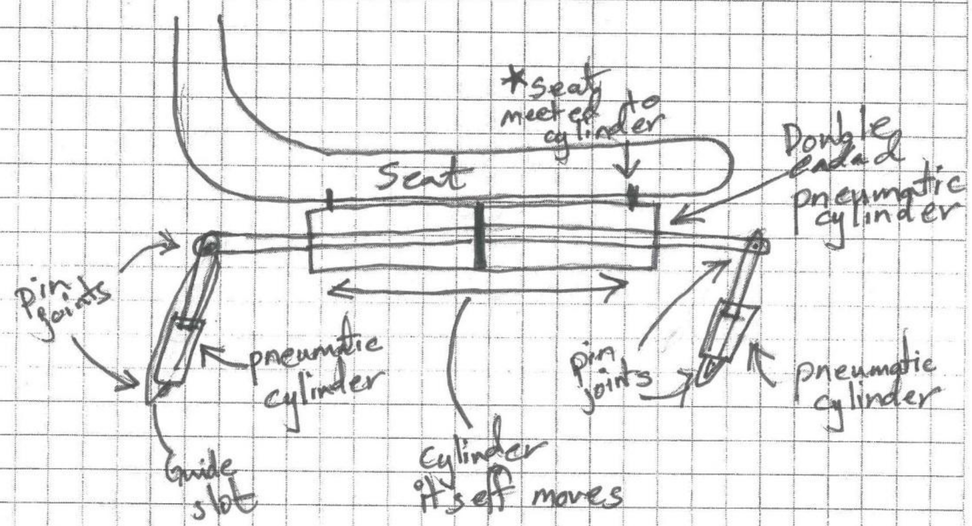


Explanation

Horizontal: Acme lead screw and ball nuts powered by electric motor

Vertical: Pneumatic cylinders powered by vehicle's vaccum lines.

XIX 3

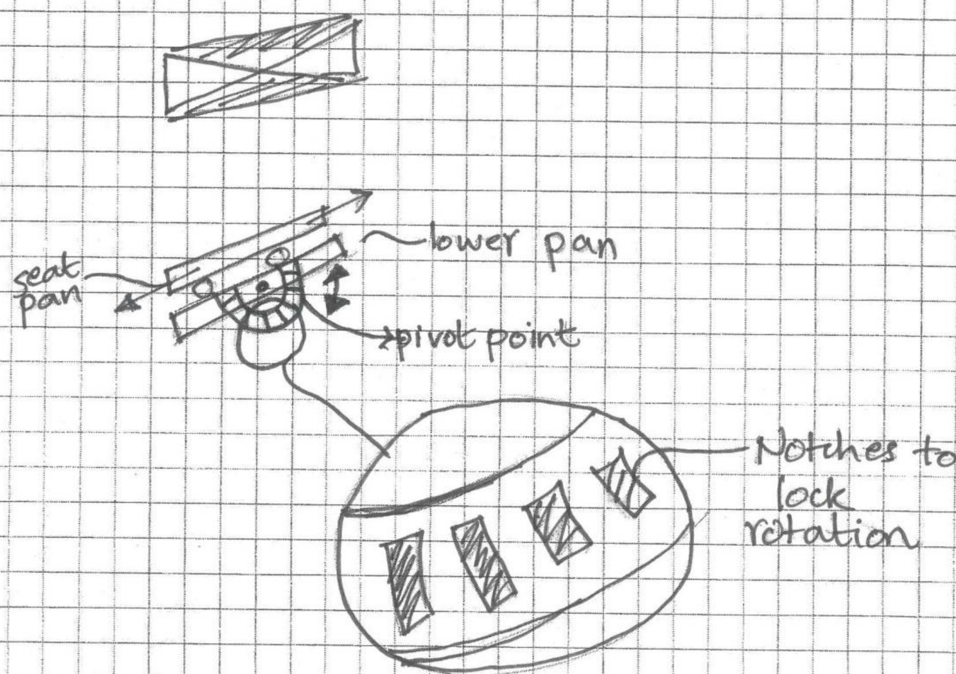


Explanation

Vertical : Pneumatic cylinder on vehicle vaccum lines.

Horizontal : Double. ended pneumatic cylinder attaled to seat,

XIX 4

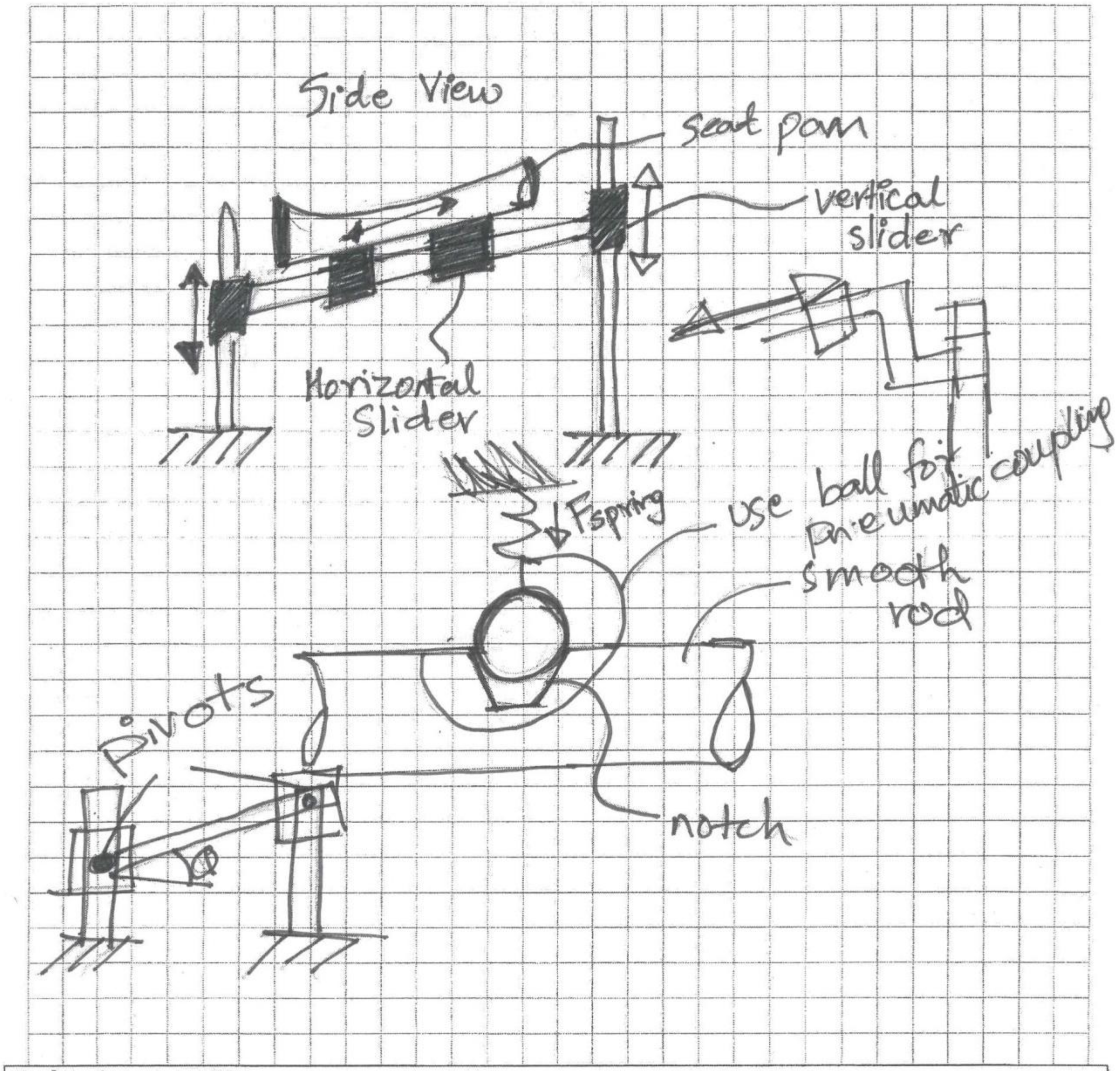


Explanation

The lower pan rotates. Notches allow the lower pan to lock into place using a hand actuated mechanism. Once the angle is selected, the seat pan can translate along a straight path parallel to the lower pan.

XV

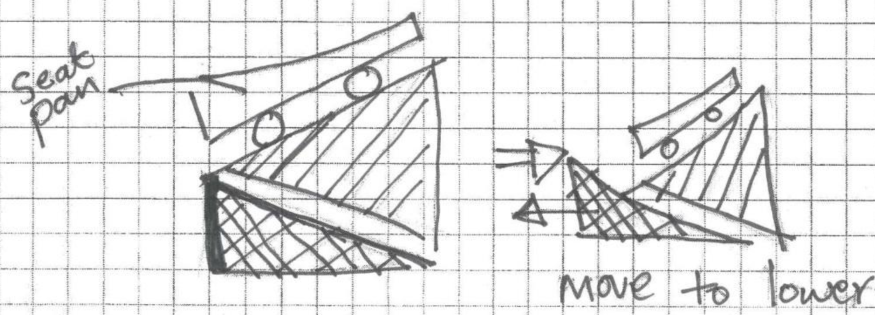
1



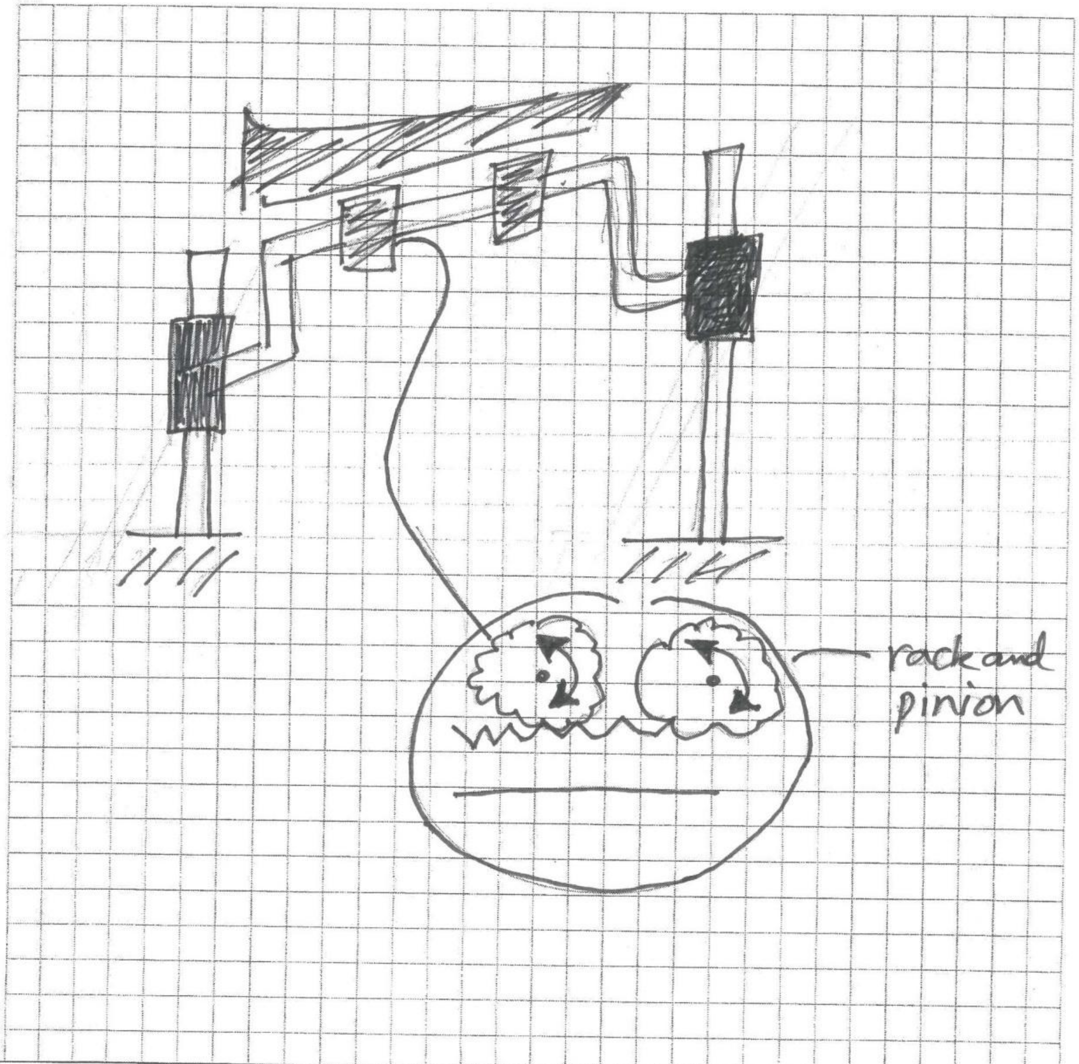
Explanation

The design uses a "gantry" system this uses two vertical and one horizontal (angled) rods to allow movement in the H-point window. The rods can be power screws ~~with~~ that rotate to move the sliders. Alternatively, notches along smooth rods could be used to lock/unlock and slide the mechanism.

XV 2



Explanation

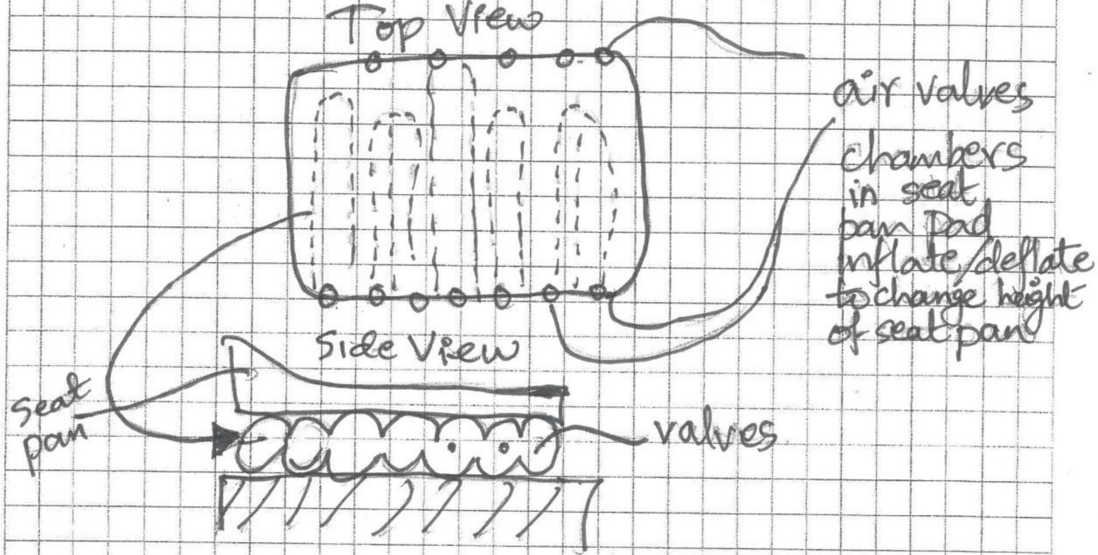


Explanation

- Same power screw design for vertical rods, "Horizontal" link B not straight to reduce the height of the vertical rods. Horizontal movement can be obtained using rack and pinion or sliding/latch mechanism

XV

4

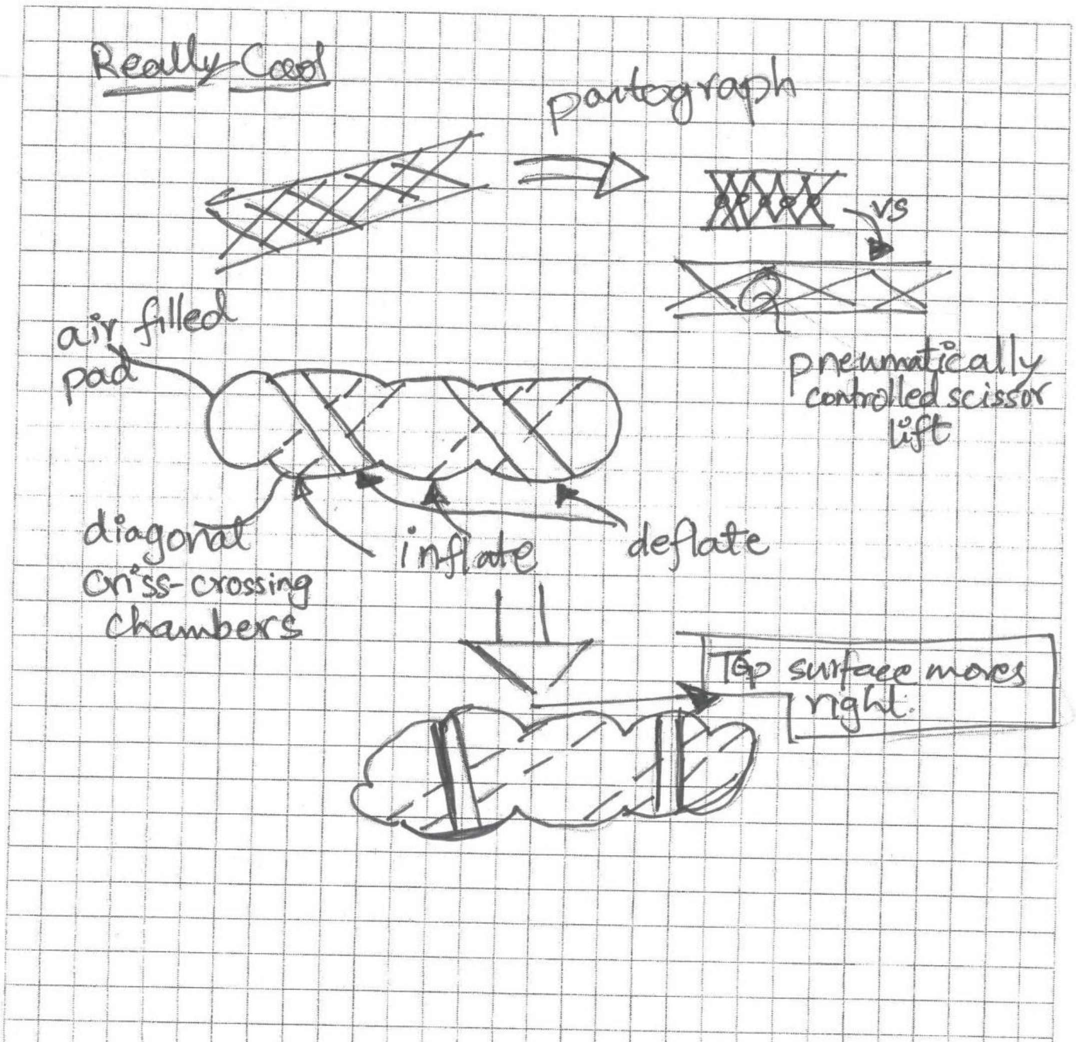


Explanation

Pneumatics inflate/deflate chambers to provide vertical motion

XV

5

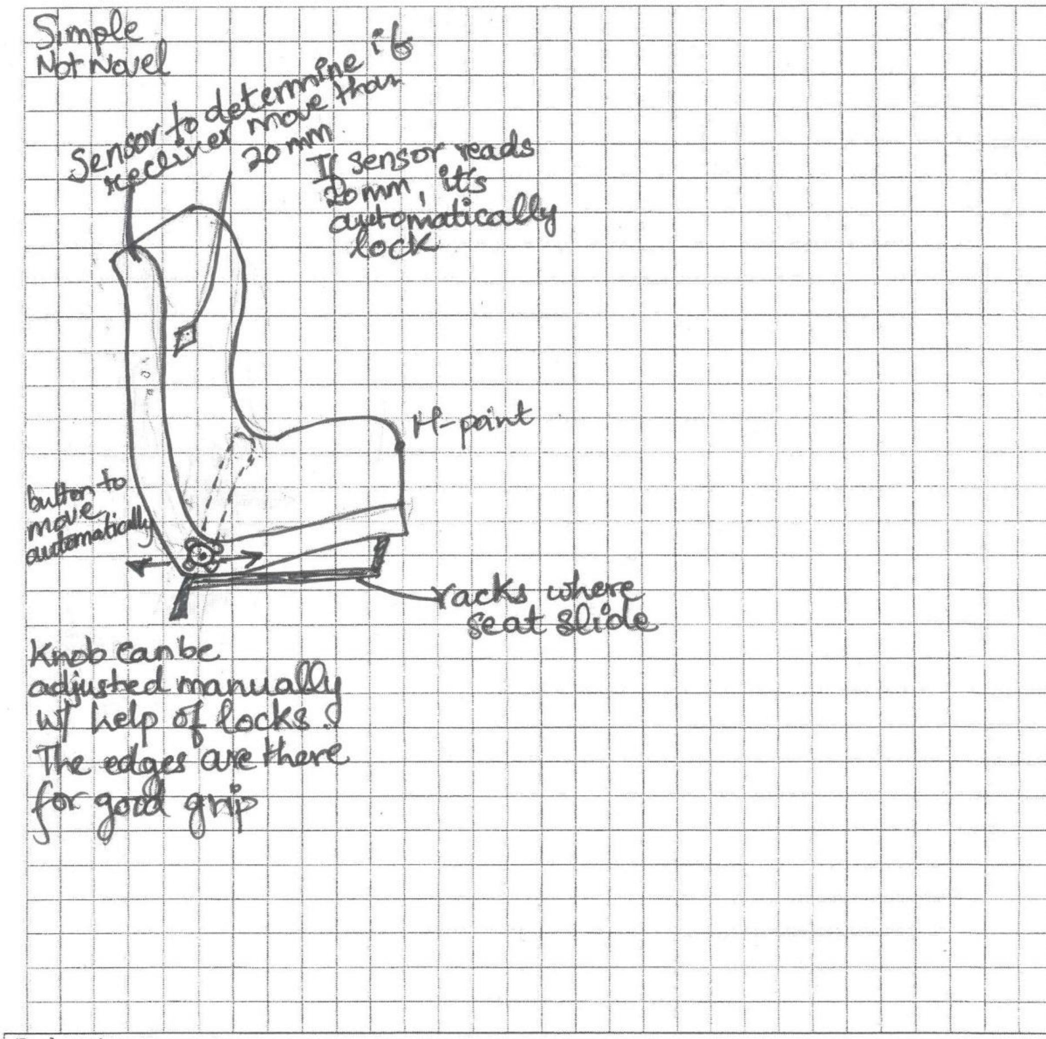


Explanation

Re-designed pnematic pads to allow for vertical/ horizontal motion without moving parts.

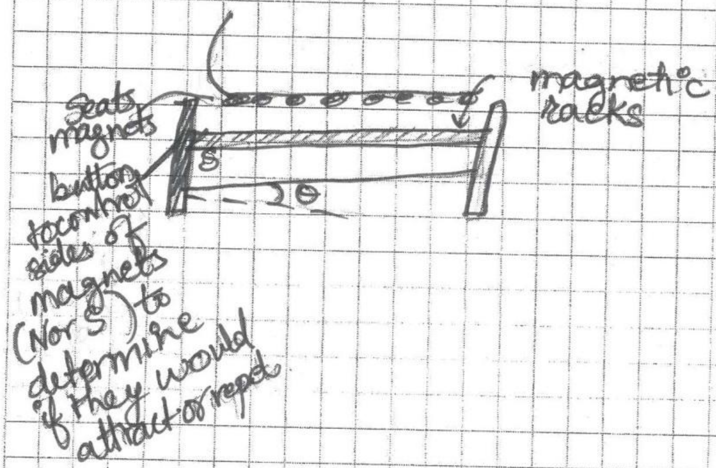
Inflate/deflate criss-crossing chambers to "shear" the entire pad, moving the top surface forward or backwards

- High air pressures needed to reduce deformation, but compression could replace seat padding
- Active control lever driver into turn.



Explanation

Simple
Novel

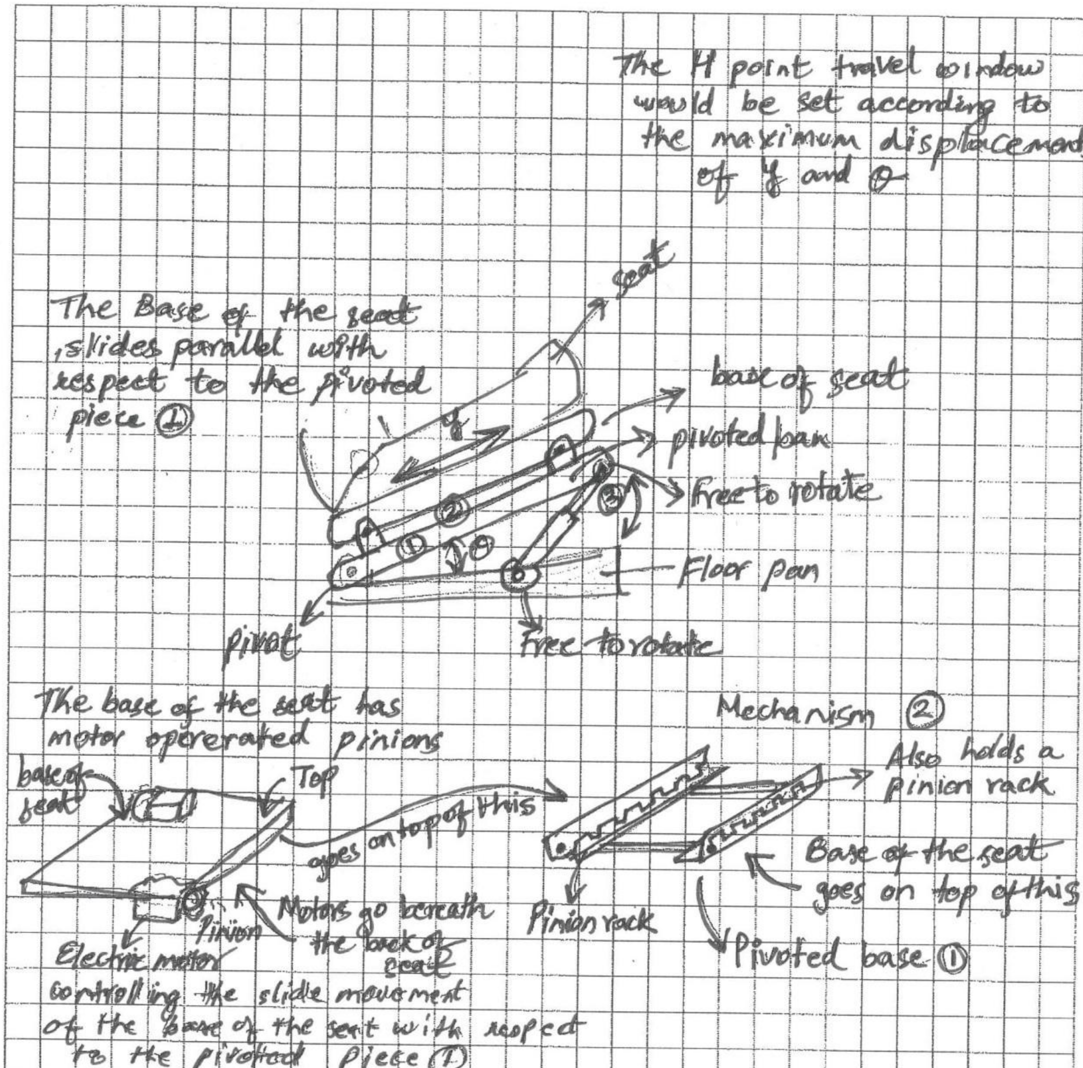


Explanation

Can adjust the angle to make it slide horizontally
θ will be greater for short people and smaller for tall people
The magnetic racks replace having holes and being limited to those only spots. Instead you have magnets that can repulse to allow user to adjust seat and when they are done the user can lock it with the same switch when the magnets have opposite poles

XII

2



Explanation

Piece ① is a pivoted base that holds mechanism ②
Actuator ③ would change the angle θ
→ motors control the rotation of pinions.
The amount of motors would be calculated according to the maximum torque needed to more the seat with the occupant
This would have to be electronically controlled..

Appendix B: Design Study II

B.1: Rubric of 0-1-3-9 scale used for initial concept evaluation in Design Study II

The rubric for scale 0-1-3-9 used for initial concept evaluation in Design Study II.is listed below in **Error! Reference source not found.**.

Requirement	**0 (Absent)**	**1 (Low)**	**3 (Medium)**	**9 (High)**
R1: Accepting can (s)	Absence of mechanism to accept can (s) for crushing	Mechanism with unstable components to hold the can(s). Insufficient information on mechanism / components holding the can. Impossible to construct or install.	Adequate information on components of mechanism. Possible to construct with minor changes, addition of new features. Needs more detailing at certain levels or aspects of mechanism.	Highly efficient mechanism with supporting information about components/ mechanism. Possible to construct, can completely work.
R2: Crushing can (s)	Absence of mechanism to crush accepted can (s)	Mechanism with unstable components to crush the can(s). Insufficient information on mechanism / components used to crush the can. Impossible to construct or install.	Adequate information on components of mechanism. Possible to construct with minor changes, addition of new features or modifications. Needs more detailing at certain levels or aspects of mechanism.	Highly efficient mechanism with supporting information about components / mechanism. Possible to construct. Doesn't require additional or supporting components.

Requirement	0 (Absent)	1 (Low)	3 (Medium)	9 (High)
R3: Height of crushed can is 15mm	No mechanism to ensure that can (s) are crushed	The mechanism crushes the can to a variable height / insufficient information to determine height of crushed can.	The mechanism crushes can to height of 15mm ± 2mm. Fairly possible to construct with additional supporting components. Might need additional information on certain aspects of the mechanism.	The mechanism ensures that the height of crushed can is less than 15mm. Possible to construct. Doesn't require additional or supporting components.
R4: Storage of can (s)	No mechanism to store crushed can (s)	Poor mechanism to store, impossible to construct, unstable components. Insufficient information on components or mechanism.	Fairly possible to construct, Possible to construct with minor changes, addition of new features or modifications. Needs more detailing at certain levels or aspects of the mechanism.	Highly efficient mechanism, completely possible to construct, doesn't require modifications to components to perform functions.

Requirement	**0 (Absent)**	**1 (Low)**	**3 (Medium)**	**9 (High)**
R5: Ease of operation	No information about mode of operation	Highly difficult to operate due to complex features or very high manual strength required. Insufficient information to access the ease of operation.	Fairly possible to operate or requires medium manual strength. Possible to construct with additional or supporting components.	Very easy to operate. Very low manual effort required, simple user interface for automated mechanism. Doesn't require additional or supporting components.
R6: Safety of operation	No mechanism to ensure safety of operation	Highly risky and unsafe to operate with high probability of personal injury. Insufficient information to access the safety of operation.	Fairly safe to operate. Needs additional supporting elements. No apparent personal injury can cause tiredness or exhaustion if instructions are not followed.	Highly safe to operate. Doesn't need additional or supporting elements.
R7: Portability	Portability not addressed, large heavy mechanisms /component	Very low portability. Large, heavy mechanism/components with some portability features like wheels. Difficult to handle. Insufficient information to access portability	Fairly compact mechanism, some modifications required to make handling easy. Requires additional supporting components and detailing of certain aspects of the mechanism.	Highly portable. No modifications required to handle.

Requirement	0 (Absent)	1 (Low)	3 (Medium)	9 (High)
R8: Accessibility of crushed can (s)	No accessibility to crushed can(s)	Poor accessibility of the crushed cans/ insufficient information on components or mechanism.	Fair accessibility to the crushed cans, needs additional or supporting components and detailing of certain aspects of mechanism.	Very easy accessibility to the crushed cans and doesn't require additional or supporting components.

B.2: Design Study II Illustrative Concept Evaluation

The following example design concepts were graded using the refined rubric scale of 0-1-3-9 listed in Table 4.3. Example 1 (See Figure 6.3) is a design concept from Set A and Example 2 (See Figure 6.4) is a design concept from the Set B. The scores for the design concepts per requirement are explained as follows:

Example 1

Figure 6.3 is used in this example to exhibit grading using the refined rubric listed in Table 4.3.

- *Accepting can (s)*: The mechanism receives the can by opening the hatch. There is adequate information on how the mechanism accepts the can(s). The mechanism seems fairly possible to construct provided additional information on opening/closing mechanism of the hatch. The rating of this concept for meeting the corresponding requirement is 3.
- *Crushing Can(s)*: There is insufficient information regarding what crushes the can inserted into the cylinder. It could be a piston operated by the lever or a plate. The

figure displays a piston like structure to crush the can once the lever is operated. Based on the rubric, the concept is rated a 1 for crushing the can(s).

- *Height of crushed can is 15mm*: The concept does not crushing mechanism or explicit features to ensure that the height of crushed can(s) is 15mm or less. Due to the lack of this information, the concept is rated a 1 for addressing this requirement.

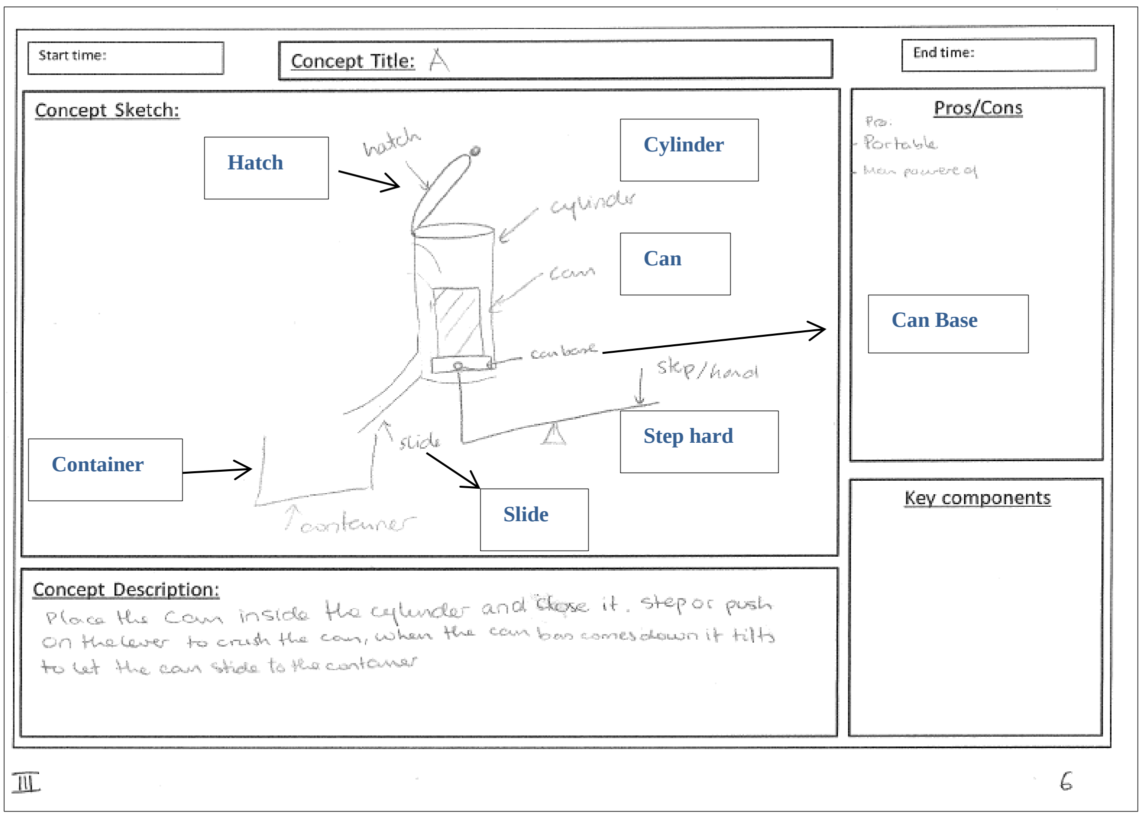


Figure 6.3: Example 1- Concept sketch from Set A of Design Study II

- *Storage of can(s)*: The sketch depicts that the crushed can would slide into a container. However, there is insufficient information to determine how the sliding takes place since there is no guide inside the cylinder to direct the crushed can into the container. The concept is rated a 1 for addressing this requirement.

- *Ease of operation:* The mechanism is activated to crush the can(s) manually by stepping on the lever. This could require very high manual strength perform the crushing operation. The concept is graded a 1 for addressing this requirement.
- *Safety of operation*: The mechanism does not seem safe to operate. The hatch can spring open during the crushing operation since information on how to keep the hatch from propping open is not provided. The manual stamping on the other end of the lever can cause injuries to the operator. Based on the rubric, the concept is graded a 1 for addressing this requirement.
- *Portability*: The sketch does not provide information on the dimensions of the mechanism or components of the mechanism. It also lacks portability features such as wheels, handles or other handling features necessary for portability. The concept is graded a 0 for addressing this requirement.
- *Accessibility of crushed can(s)*: The sketch depicts the crushed can(s) would be collected in the container outside the cylinder. The crushed can(s) can be fairly accessed from the open container but this can create problems if the container is about to get filled completely. It requires supporting components to improve accessibility under such conditions. The concept is graded a 3 based on the rubric for addressing this requirement.

Example 2

Figure 6.4 is used in this example to exhibit grading using the refined rubric.

- *Accepting can (s)*: The sketch does not provide information on how the mechanism accepts can(s). Based on the rubric, the concept is rated a 0 for addressing this requirement.

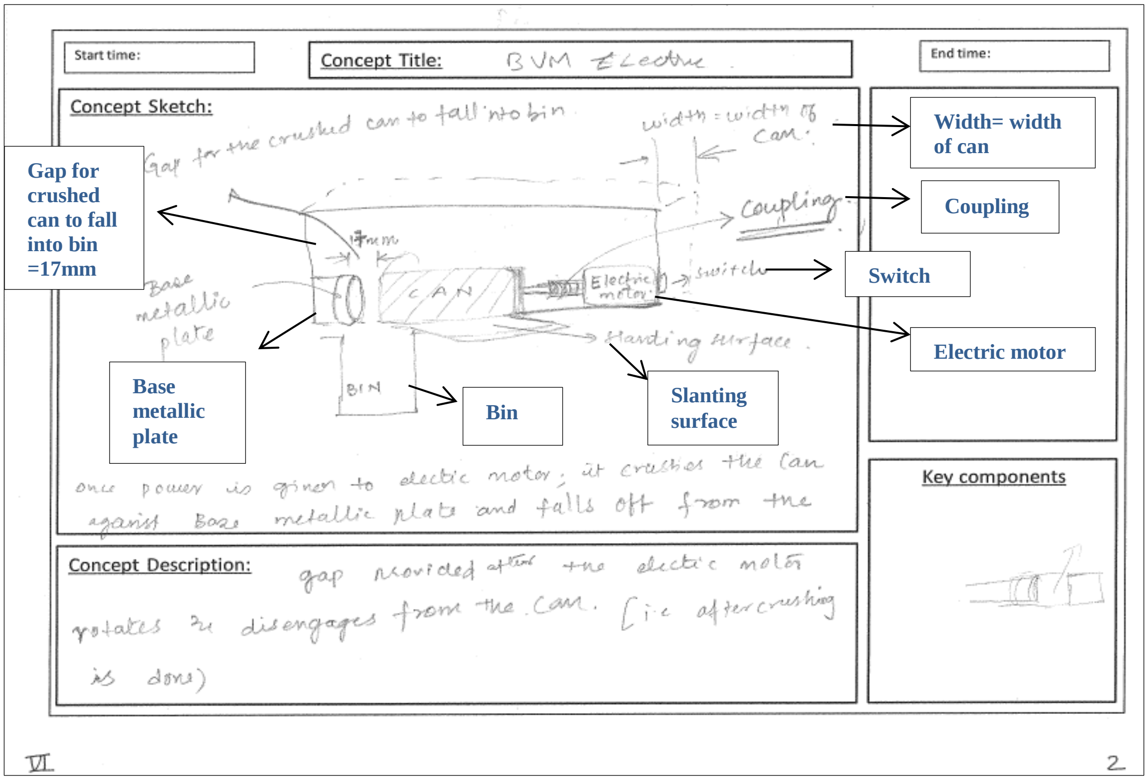


Figure 6.4: Example 2- Concept sketch from Set B of Design Study II

- *Crushing Can(s)*: The can is crushed between two metallic plates, one of them is actuated by an electric motor. This is an efficient mechanism for crushing the can, therefore the concept is graded a 9 for addressing this requirement.

- *Height of crushed can is 15mm*: The can is crushed between the plates upto 17mm. The movable plate seems to travel forward until the space between the two plates is 17mm. Based on the rubric, the concept is graded a 3 for addressing this requirement.

- *Storage of can(s)*: The crushed can(s) are stored in a bin. However, the gap of 17mm might not be sufficient for the can to fall through the gap provided. The mechanism requires additional information or components to address the problem. The concept is rated a 3 for addressing this requirement.
- *Ease of operation*: The mechanism is actuated by a switch that starts the electric motor. This is both very easy to operate and requires very low manual effort. The concept is graded a 9 for addressing this requirement.
- *Safety of operation*: The mechanism is closed keeping the motor and components out of reach from the operator. The direction of operating switch is opposite to the crushing direction of the mechanism which makes the operation safer for the operator. Based on the rubric, the concept is rated a 9 for addressing this requirement.
- *Portability*: The sketch lacks portability features such as wheels, handles or other handling features necessary for portability. The concept is graded a 0 for addressing this requirement.
- *Accessibility of crushed can(s)*: The crushed can(s) will be collected in the bin outside the cylinder. The crushed can(s) can be fairly accessed from the open bin but can be troublesome when the bin is about to get or filled completely. It requires supporting components to improve accessibility under such conditions. The concept is graded a 3 based on the rubric for addressing this requirement.

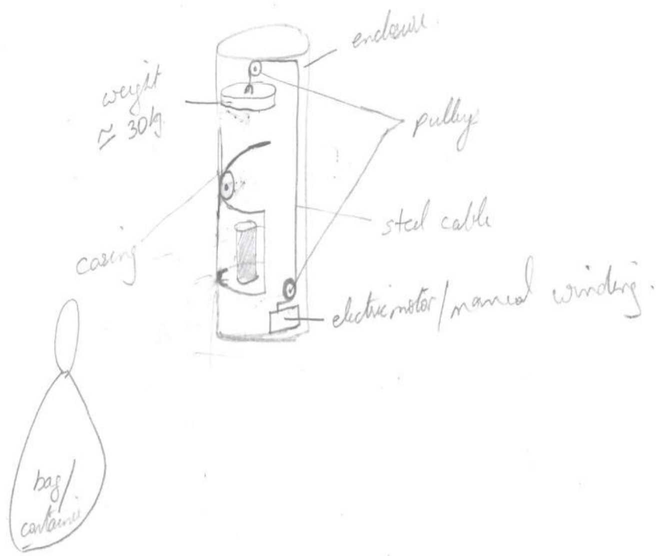
B.4: Design Study II Concept Sketches

Start time:

Concept Title: Dropping weights

End time:

Concept Sketch:



Pros/Cons

+) Light

+) Simple

-) Electric motor (Power is a problem for portability)

-) Weight dropping onto casing could break it / casing needs to be strong.

-) Impact could throw m/c off balance.

Key components

Electric motor, weight, flexible casing

Concept Description: Coffee-maker type of shape for enclosure. Motor drives a pully up. Button drops weight onto can to crush. Man removes crushed can to container manually. For safety, a casing is present around opening to place can. The casing slides up/down. Weight falls down only when casing is down because casing rolls up (flexible) into path of weight in 'up' position.

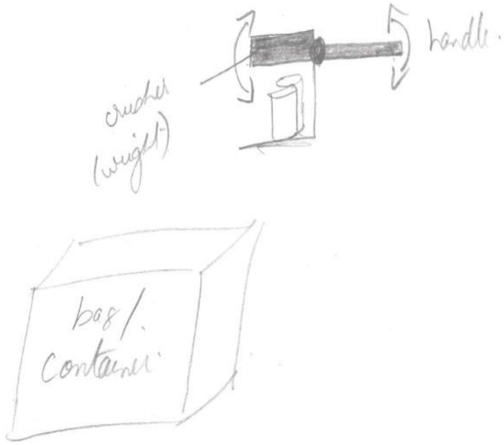
V

Start time:

Concept Title: Lever mechanism.

End time:

Concept Sketch:



Pros/Cons

+) Simple
+) Reliable
-) Safety is an issue
+) Can be automated by using an actuator to move lever/ weight.

Key components

Concept Description: handle at one end, weight at other end. Manual crushing of can(s). Manual transfer to container.

V

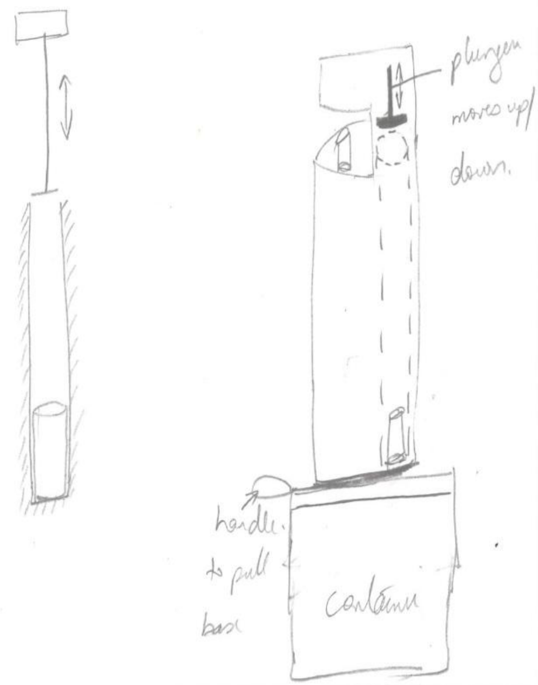
2

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

+) Safe

-) Portability?

-) What moves the plunger?

Key components

Plunger

tube / slot

base plate.

(moveable)

Concept Description:

Plunger moves up/down to crush can. (pulley & weight or straight rod plunger). User pushes can to slot, can drops, plunger crushes can, user pulls handle to open base & drop crushed can to container. Plunger motion can be manual / controlled electronically by some means.

V

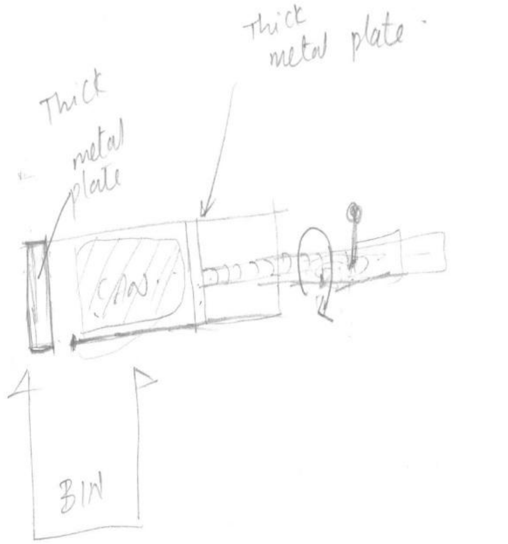
13

Start time:

Concept Title: Bench vice mechanism

End time:

Concept Sketch:



Pros/Cons

+) Manual
+) Safe
+) easy disposal

Disadvantage
1 can at a time.

Key components

Concept Description: This is like a bench vice mechanism. The user places the can and rotates the handle. after the can is crushed, the crushed can falls into the bin through the slot provided.

VI

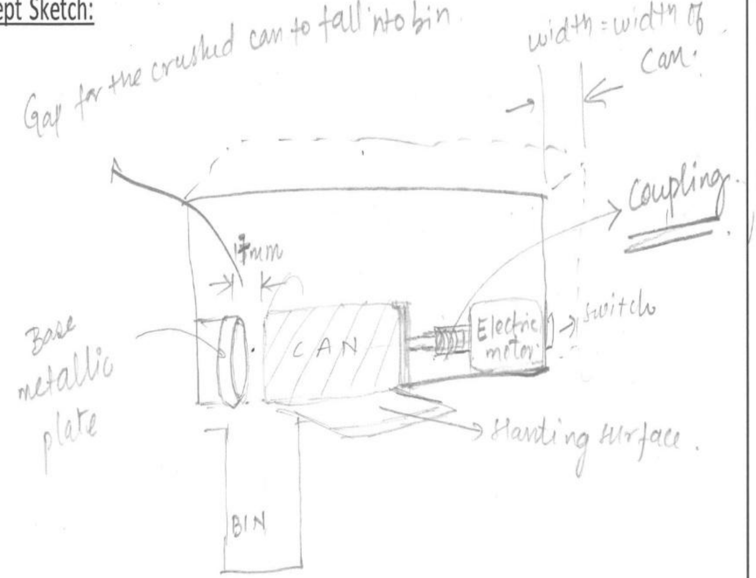
3

Start time:

Concept Title: BVM Electric.

End time:

Concept Sketch:



once power is given to electric motor; it crushes the can against Base metallic plate and falls off from the

Pros/Cons

Key components

Concept Description: gap provided after the electric motor rotates & disengages from the can. [i.e after crushing is done)

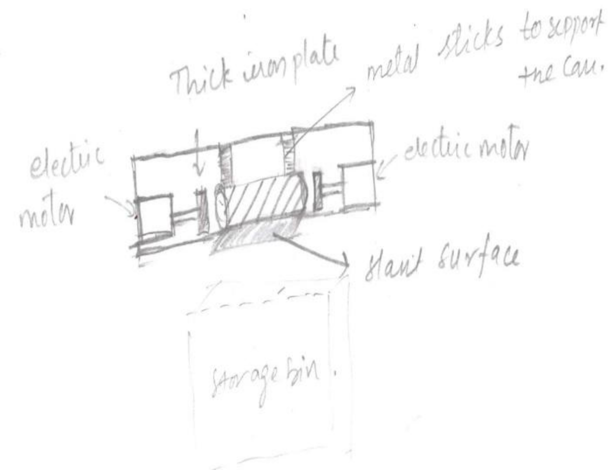
VI

Start time:

Concept Title:

End time:

Concept Sketch:



The can is slided over the slant surface. The other side is hollow. Two thin metal strips prevent it from falling on the other side.

Pros/Cons

Portable

Key components

Concept Description:

once the electric power is given to the motors, they engage with the can simultaneously and hold it. Require pressure/force is given untill it reaches 15 mm. once the crushing is done, the motion to electric motors can be given in opposite direction and this will automatically throw the can out to a storage bin placed on the other side because the height of can is no more than the space between the metal sticks.

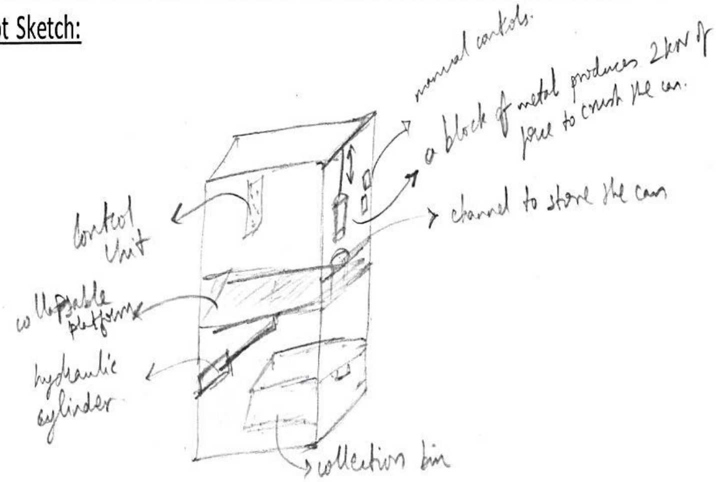
VI

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

1.) An efficient method.
2.) Simple concept
3.) Easy to operate.
4.) The collection bin is retractable

Cons

1.) The mechanism may not be so portable.

Key components

Concept Description: 1.) The aluminium can is placed in the channel and a button is pressed to initiate crushing. 2.) A metal cylindrical block moving vertically crushes the can by producing 2kN of force. This is a hydraulic cylinder. 3.) After the cylinder retracts, it activates the other cylinder to collapse the platform and the crushed can falls down. The cylinder gets back to its normal position again. 4. The cylinders are controlled using electronic control units like PLCs.

VII

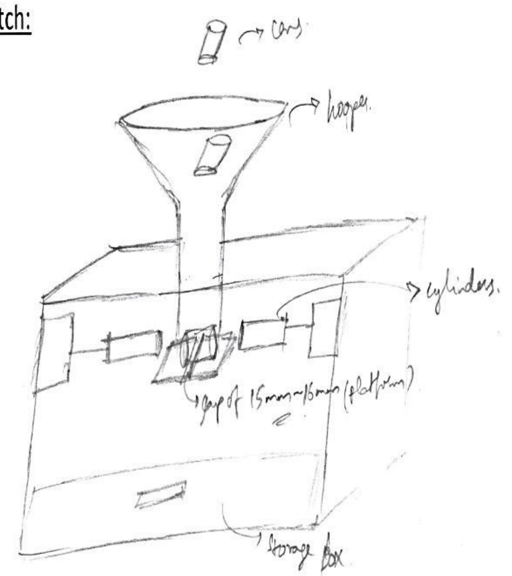
1

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

1.) Simpler design.
2.) Portable
3.) Automatic & safe to operate
4.) Storage box is removable.

Cons.

1.) Installation might be difficult initially.

Key components

Concept Description: 1.) The cans are disposed in the hopper and it is shaped in such a way that the can always falls horizontally & longitudinally 2.) There are 2 cylinders either pneumatic or hydraulic placed opposite to each other. 3.) As the can falls; it is sensed and the cylinders are actuated. The opposing forces crush the can. 4.) The platform has a gap of 15-17mm at the center, so the can after crushed falls into the storage bin. 5.) The cylinders retract again to repeat the cycle.

VII

2

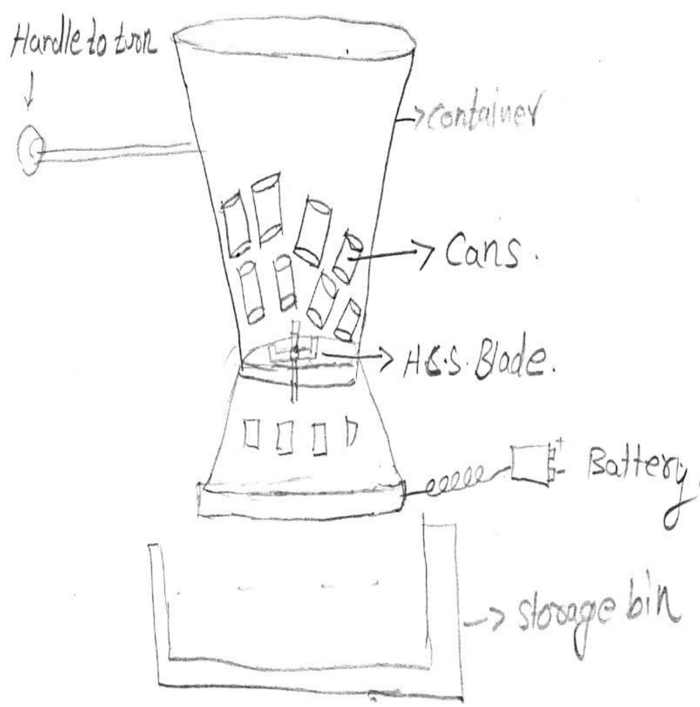
Very good (1)

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Cons:

The H.C.S blades are costly.

Key components

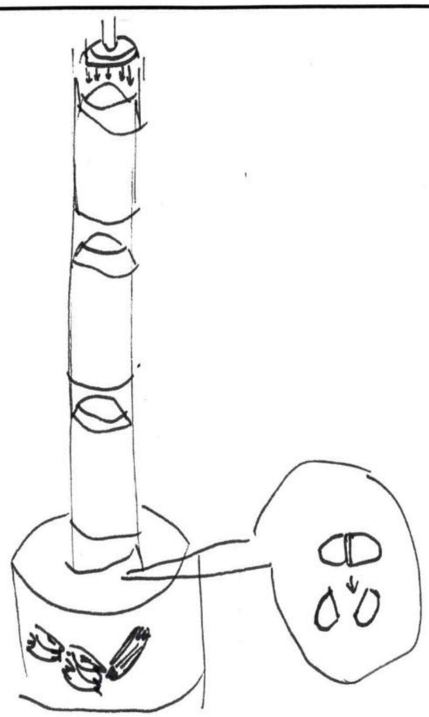
Concept Description: 1) It is similar to the grinder & mixer but this has very High carbon steel blades, which are cut the can very easily.
Then we have a handle which lifts the container to transfer the crushed into the storage bin

L 1

I.4

Start time:	Concept Title: multi can crushing	End time:

Concept Sketch:



Pros/Cons

Key components

Concept Description:

use a cylinder to store multiple cans
and crush all at the same time
flap door opens to store the crushed cans

N

4

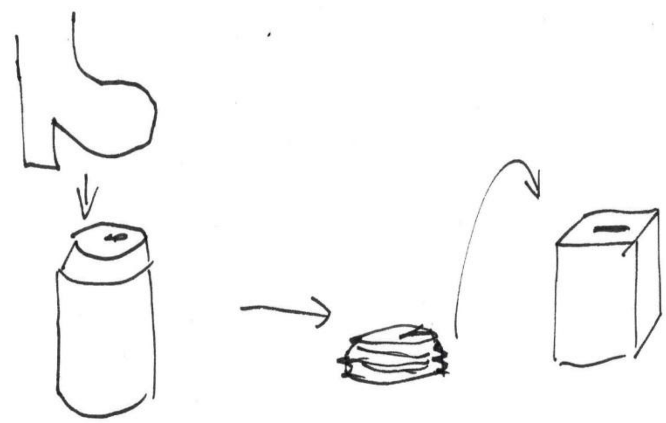
I.3

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Key components

Concept Description:

Stomp onit

N

3

I.2

Start time:

Concept Title:

End time:

Concept Sketch:

Pros/Cons

Key components

Concept Description:

Roller design similer to sheet metal production

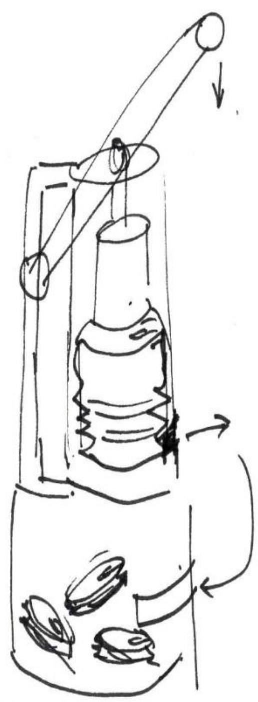
N

2

I.1

Start time:	Concept Title: Articulated:	End time:

Concept Sketch:



Pros/Cons

Key components

Concept Description:

pull the ~~bad~~ bar down and it spit out the crushed can and move it to the storage container through the slot

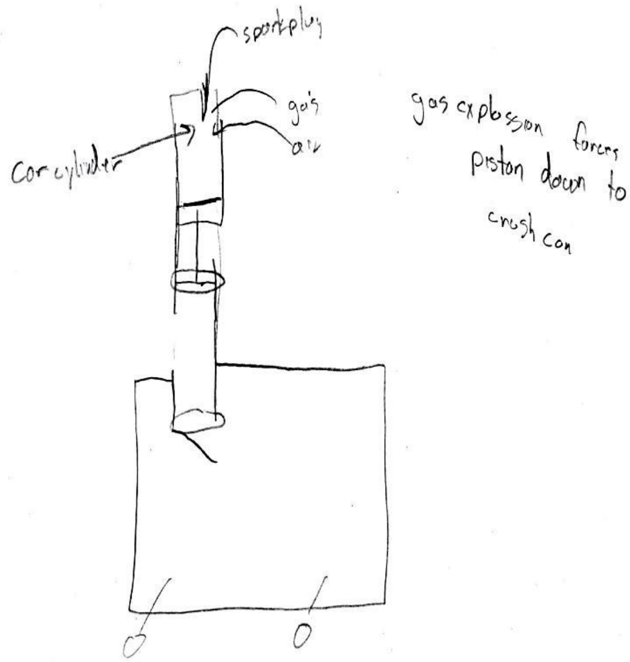
N 1

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Not Manual

Key components

Concept Description:

IV

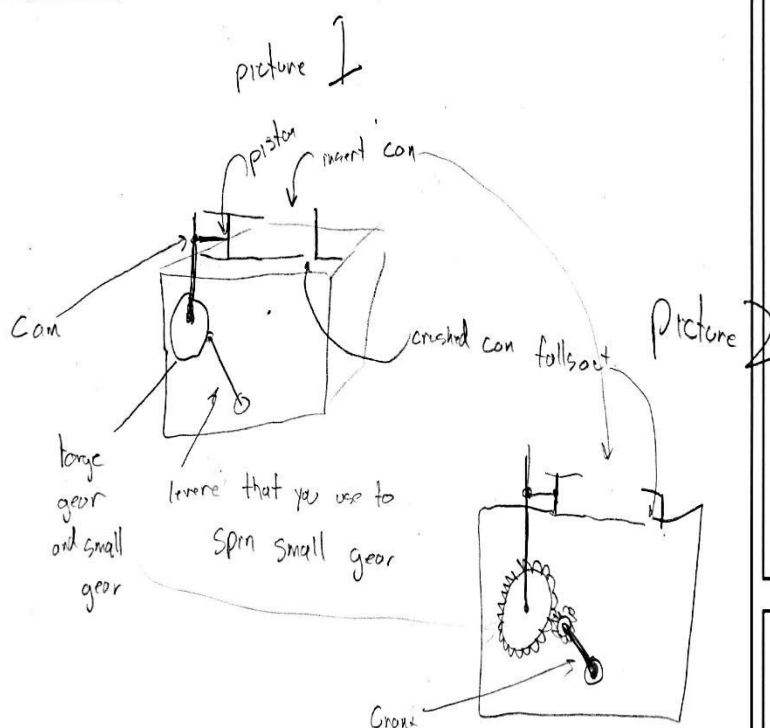
8

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Slow

Key components

Concept Description:

IV

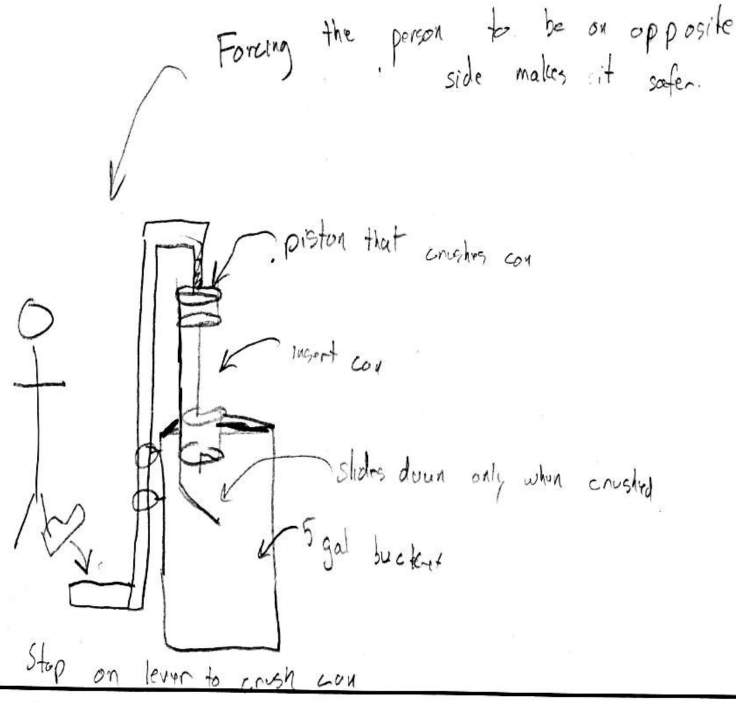
7

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Key components

Concept Description:

IV

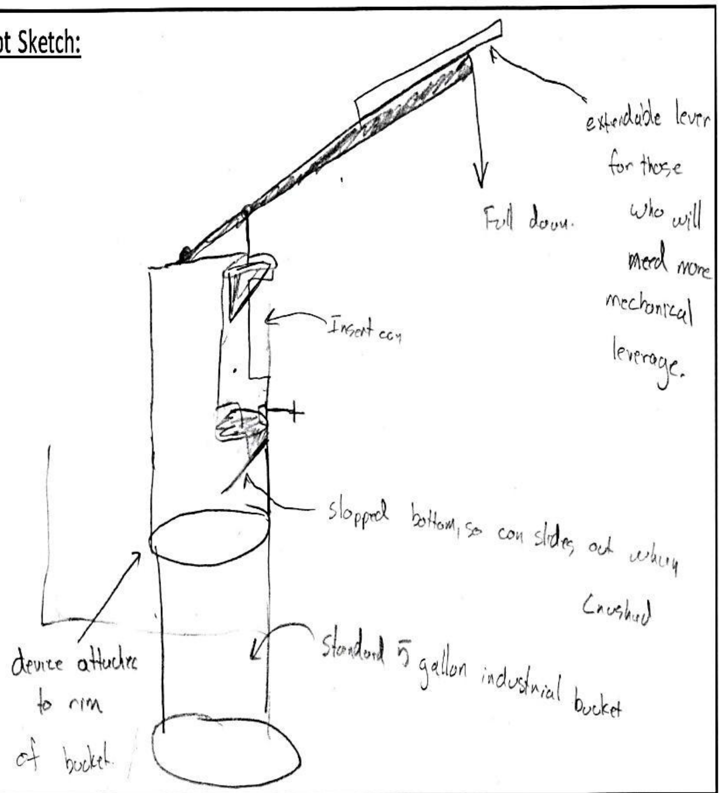
6

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Simple

Key components

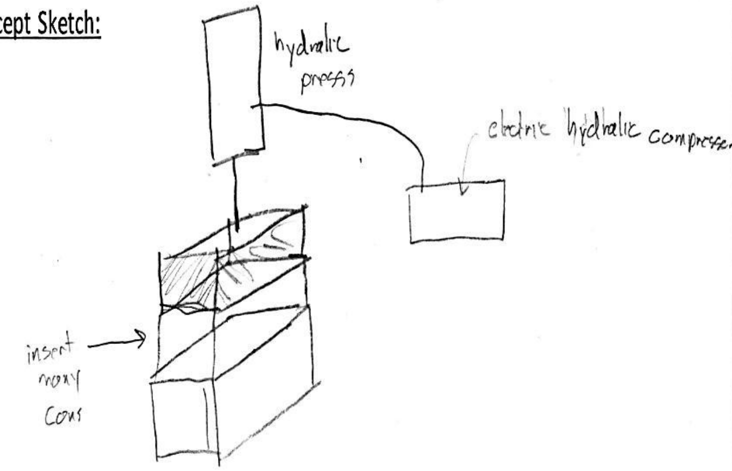
Concept Description:

IV

5

Start time:	Concept Title:	End time:

Concept Sketch:



Pros/Cons

– Not Manual

Key components

Concept Description:

N

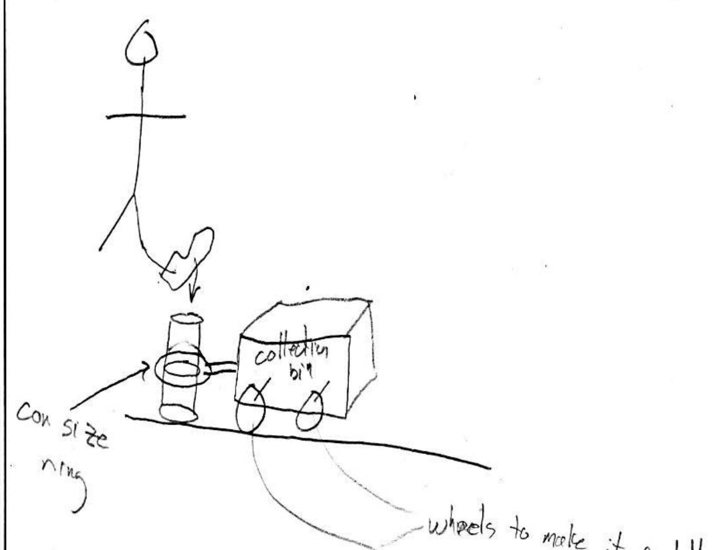
4

Start time:

Concept Title:

End time:

Concept Sketch:



1. Insert can into ring to hold it in place
2. Jump on the can
3. Pick the can up and put it in the bin.

Pros/Cons

Touch

Concept Description:

Key components

IV

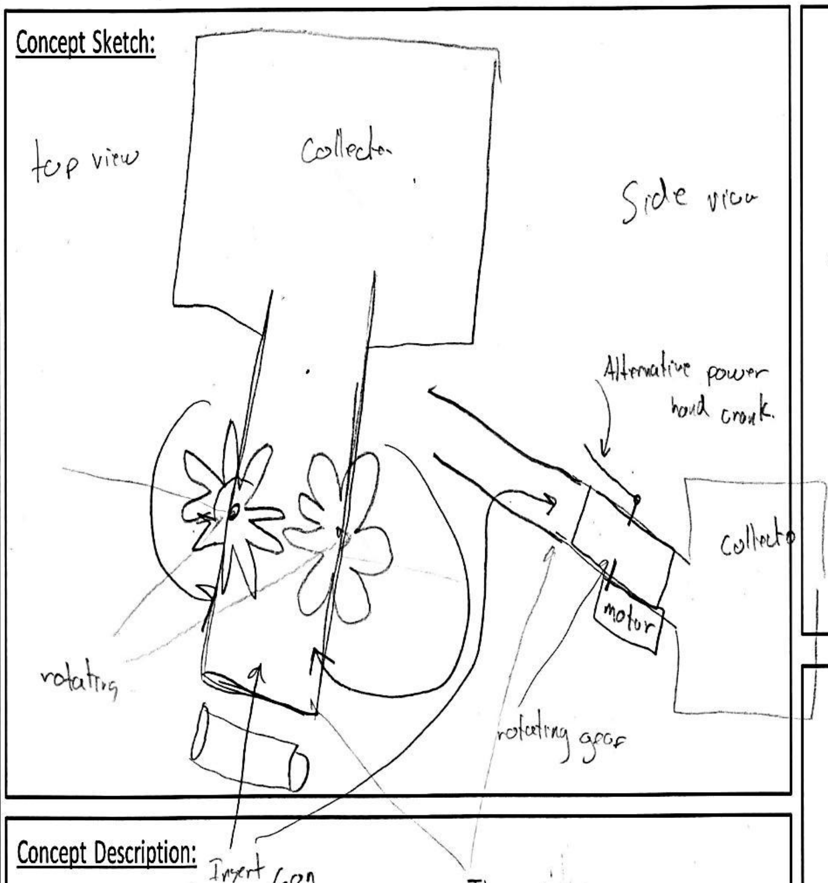
3

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

- Not Safe
- will work?

Key components

Concept Description:

The shoot that accepts the con, is con size so that it goes in straight.

IV

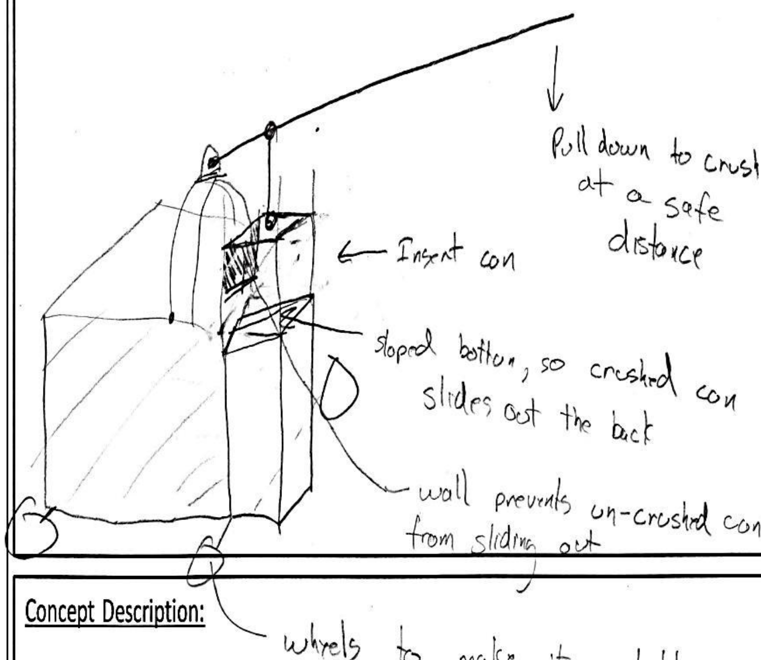
2

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

auto fail

Concept Description:

Key components

See improved version

IV

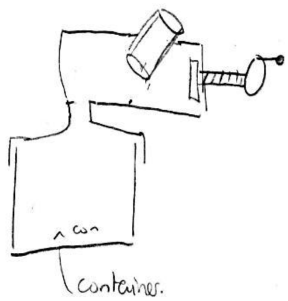
1

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Key components

Concept Description:

same as 'B' → without the hatch.

III

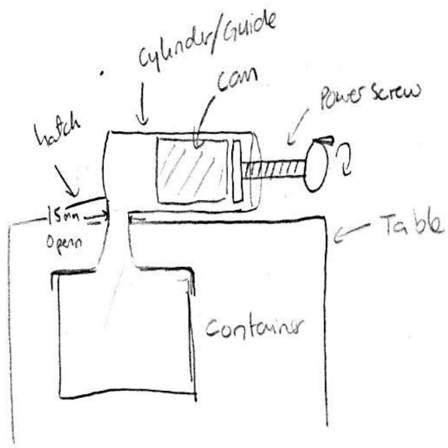
7

Start time:

Concept Title: B

End time:

Concept Sketch:



Pros/Cons

Con:
- manual → slow
- one by one

Slow.

Key components

Concept Description:
Store the can inside the cylinder, close the hatch turn power screw until crushed can fall through the 15mm opening.

III

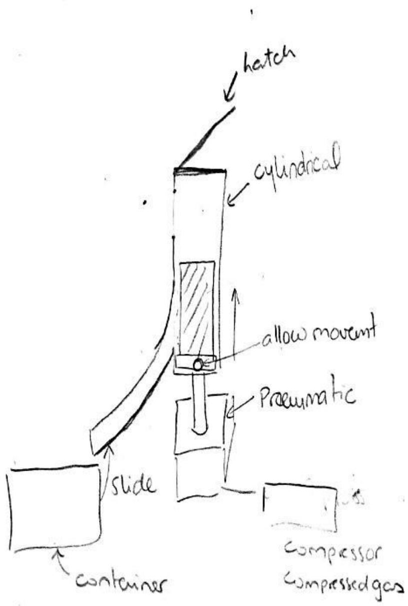
5

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Key components

Concept Description:

Similar to "A" but pneumatic.

III

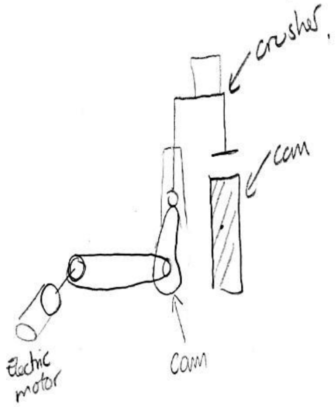
4

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Key components

Concept Description:

III

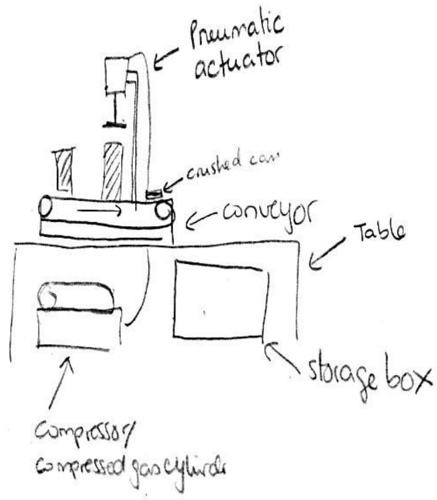
3

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Pro

- The conveyor automates the process
- The can is manually placed & every thing else is automated

Cons:

- requires controls, sensors,
- compressor increases weight & cost.

Key components

Concept Description:

The can is placed manually over the conveyor which moves it to the next position where it is crushed.

The conveyor takes & Drops the crushed can into the storage bin/box

III

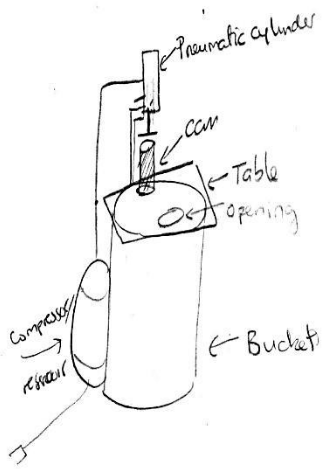
2

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

- Compresor → changed to a compressed gas cylinder
- Pneumatic components could increase cost.
- compressor limits the portability

Key components

- Bucket (

Concept Description:

Using a Bucket for crashed cans storage and a pneumatic actuator to crush the cans. the crushed can should be manually removed and dropped through the bucket opening.
The bucket is like those used to store paint.

III

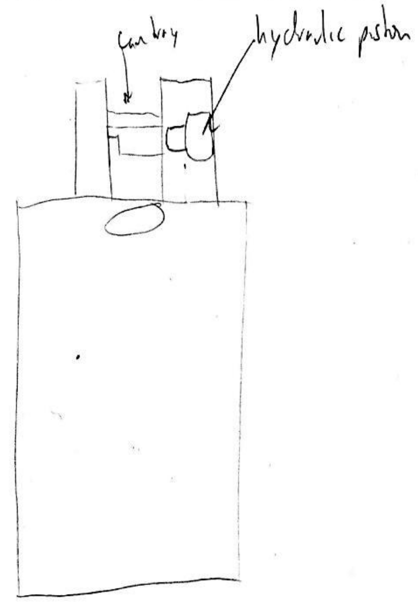
|

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Key components

Concept Description: Lay can on tray (half cylinder).

II

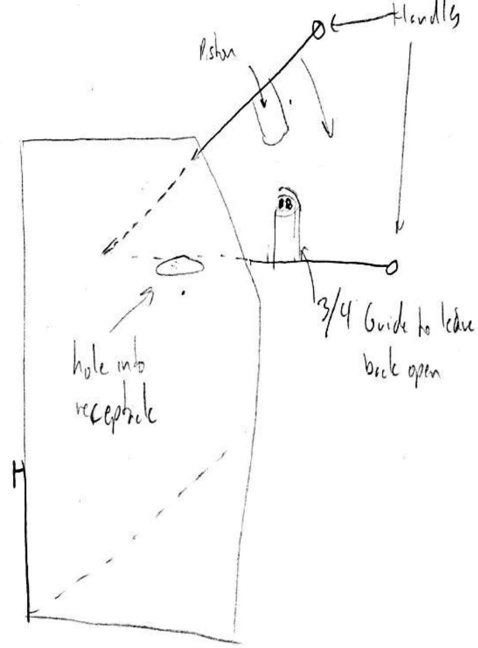
5

Start time:

Concept Title:

End time:

Concept Sketch: (Alteration of concept 1)



Pros/Cons

Key components

Concept Description: Can placed in guide. Pull top handle to crush. Lift bottom handle to slide can into receptacle

II

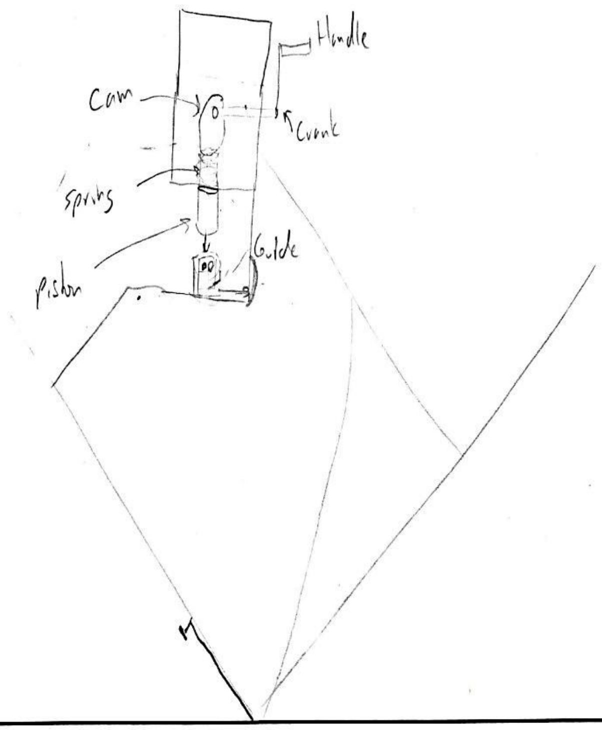
4

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Key components

Concept Description: Place can in guide. Turn handle to rotate cam, drive piston into the guide and crush the can. Once can is crushed, can slides through slot in guide, falls into receptacle

II

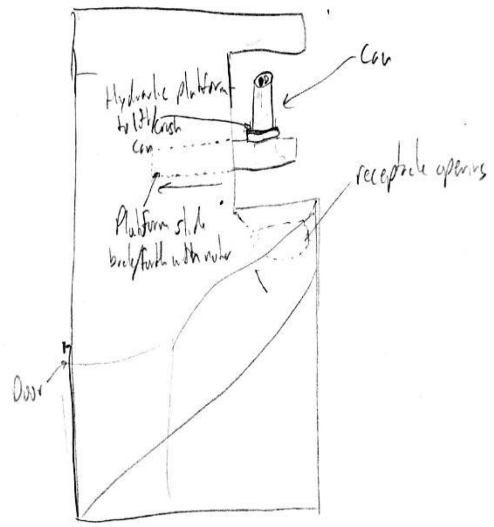
3

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Guide
Does not require manual removal

Key components

Concept Description:

II

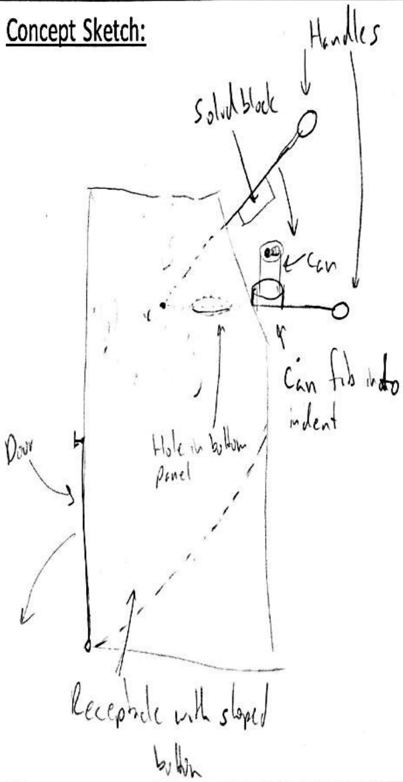
2

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Key components

Concept Description:

Can is placed into indent on bottom panel. Use top handle to crush can with solid block. Return top handle to up position. Lift bottom handle to slide can into hole and into receptacle. Cans retrieved by opening rear door.

II

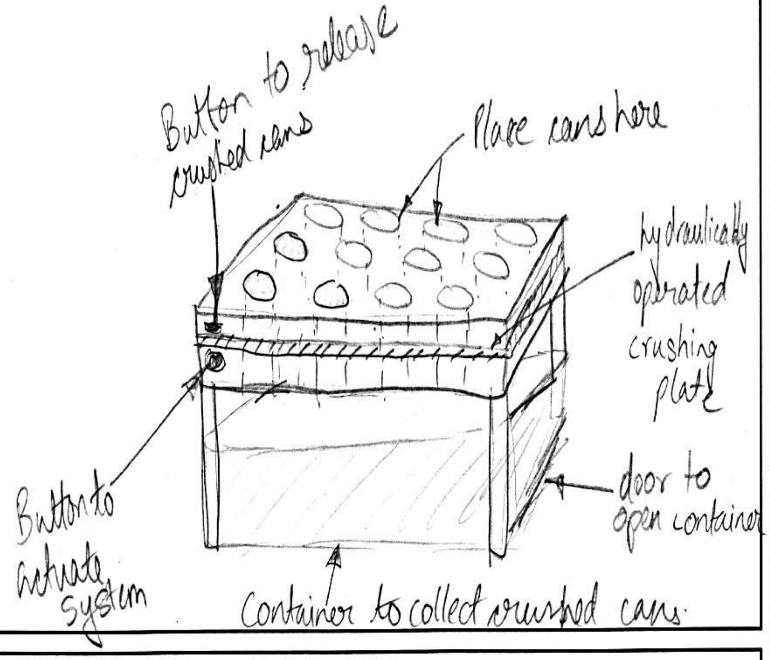
1

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Concept Description:

This concept is for applications where large number of cans will have to be crushed often. The storage container stores large number of crushed cans.

Key components

I

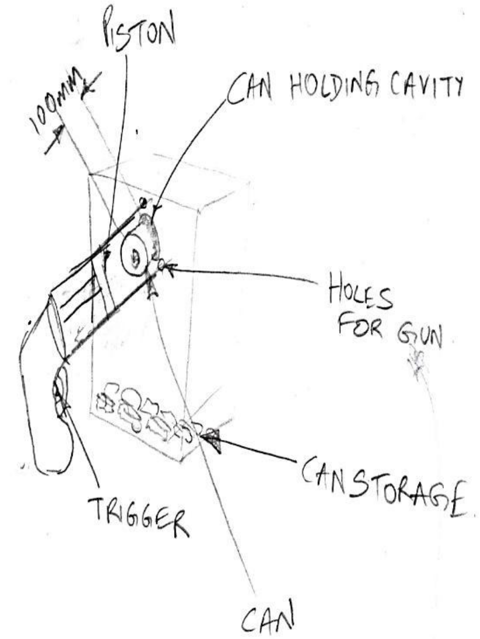
2

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Key components

Concept Description: The can holding cavity will tightly hold the can in place. The trigger will spark the fuel in the piston cylinder. NOTE: The gun end fits tightly into the "holes for gun". Upon disengaging the gun from the holes, a mechanism is triggered to release the can into storage. The crushed cans may be removed from a door (not shown).

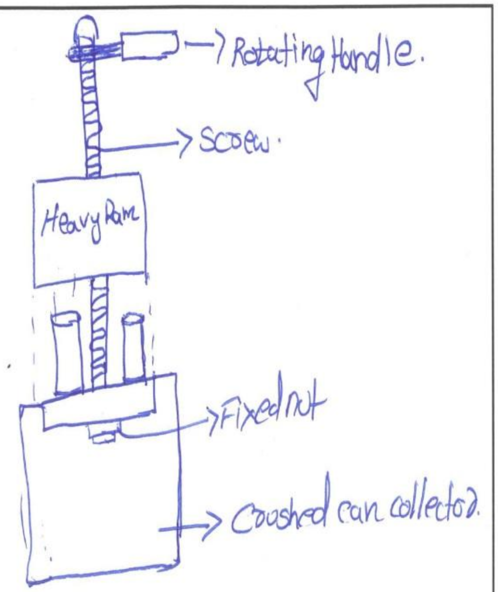
OK - 3

Start time:

Concept Title:

End time:

Concept Sketch:



Pros/Cons

Key components

Concept Description: This works on the principle of screw nut mechanism, as we rotate the handle the Heavy Ram goes down and crushes the cans.
The crushed cans are then collected in the collector beneath the surface of the ~~Ra~~ Fixed Post

L

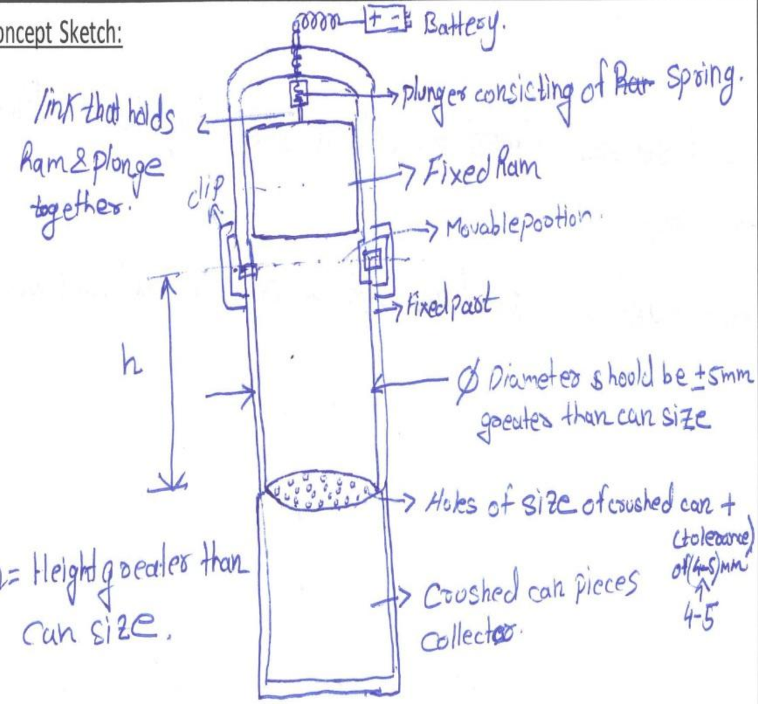
3

Sri Ram Mohinder C.V. M.E-870 (student)

Good -2 (Turn Back) for Advantages

Start time:	Concept Title:	End time:

Concept Sketch:



Pros/Cons

Pros:
- Easily manufacturable
- Portable
- simple design.

Cons:
1) Spring force ≥ 2kN which might be expensive
2) Doubtfull about the feasibility of spring mechanism

Key components

Concept Description: 1) First place the can in fixed part.
2) Then above the fixed part place the movable portion & clamp.
3) Actuate the spring in the plunger with the help of Battery.
4) The plunger or the spring produces Force of 2kN.
5) Then the Fixed Ram attached to the plunger crushes the can.
6) The crushed pieces of the can are collected at bottom due to gravity from the pores at the bottom.

2

B.3: Concept Evaluation Scores for Design Study II Concepts

	R1	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**
I-1	1	1	1	3	9	3	1	0
I-2	3	3	1	3	9	9	9	0
II-1	3	1	1	3	1	9	1	0
II-2	3	3	1	3	9	9	9	0
II-3	3	3	1	3	3	9	3	0
II-4	3	1	1	3	1	9	3	0
II-5	1	1	1	3	3	0	3	0
III-1	3	3	1	3	9	9	9	1
III-2	3	3	1	3	9	1	9	1
III-3	1	1	1	0	9	0	0	0
III-4	3	3	1	1	9	3	3	1
III-5	3	3	1	3	3	1	3	0
III-6	3	3	1	1	3	3	3	0
III-7	3	3	1	1	3	3	3	0
IV-1	3	3	1	3	3	9	3	3
IV-2	9	3	1	3	9	9	9	1
IV-3	1	1	1	3	1	9	1	3

	R1	R2	R3	R4	R5	R6	R7	R8
IV-4	3	3	1	3	9	9	9	0
IV-5	3	3	1	3	3	9	3	3
IV-6	9	9	9	3	1	9	9	3
IV-7	3	3	1	3	3	1	3	0
IV-8	3	3	1	3	9	3	3	3
V-1	9	9	3	9	9	9	9	9
V-2	3	9	3	9	3	9	3	0
V-3	9	9	3	9	3	9	3	0
VI-1	3	9	1	3	3	3	3	0
VI-2	3	9	9	3	9	9	9	0
VI-3	3	3	9	9	9	9	3	0
VII-1	3	3	1	3	9	9	9	1
VII-2	1	3	1	3	9	9	9	1
VIII-1	3	3	3	9	9	3	3	0
VIII-2	3	3	1	9	3	3	3	0
L-1	0	0	0	0	0	0	0	0
L-2	3	3	9	3	9	0	1	0
L-3	3	3	1	1	3	0	3	0

	R1	R2	R3	R4	R5	R6	R7	R8
N-1	3	1	1	3	1	0	3	0
N-2	1	1	1	1	1	0	0	0
M-1	1	1	1	1	1	3	1	0
M-2	3	1	1	1	3	0	1	0

Appendix C: Facilitated Ideation Workshop Survey Results

Question 1: Please select the category that best describes your familiarity with ME 402 team members. Select all that are applicable.

Table 6.2: Percentage response to Question 1

Question 1 Percentage Response	
Friends	50%
Classmates	44%
Acquaintances	6%

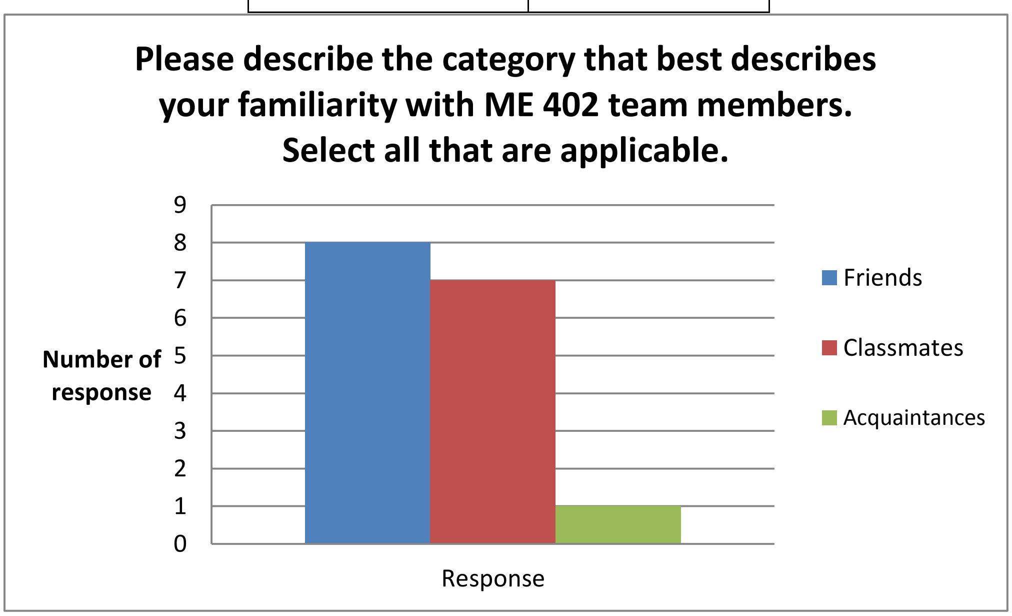


Figure 6.5: Response for Question 1

Question 2: If selected 'friends' or 'acquaintance' for Question 1, how long have you known each other? Choose only one.

Table 6.3: Percentage response to Question 2

Question 2: Percentage Response	
More than a year	70%
One year	0%
less than 6 months	30%

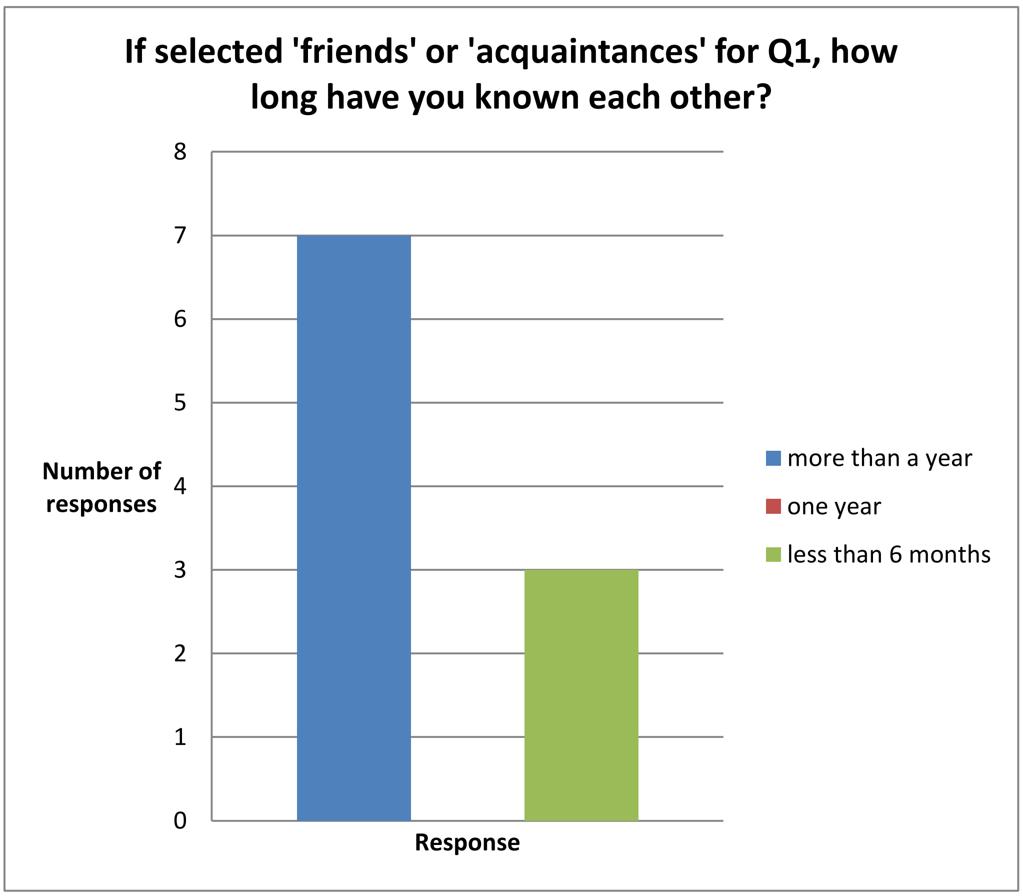


Figure 6.6: Response for Question 2

Question 3: If selected 'friends' or 'acquaintance' for Question 1, how has this affected your performance during the ME 402 facilitated hybrid ideation workshops? Choose only one.

Table 6.4: Percentage response for Question 3

Question 3 Percentage Response	
Has mildly enhanced my performance	50%
Has strongly enhanced my performance	10%
Has mildly reduced my performance	0%
Has strongly reduced my performance	0%
Has no effect in enhancing or reducing my performance	40%

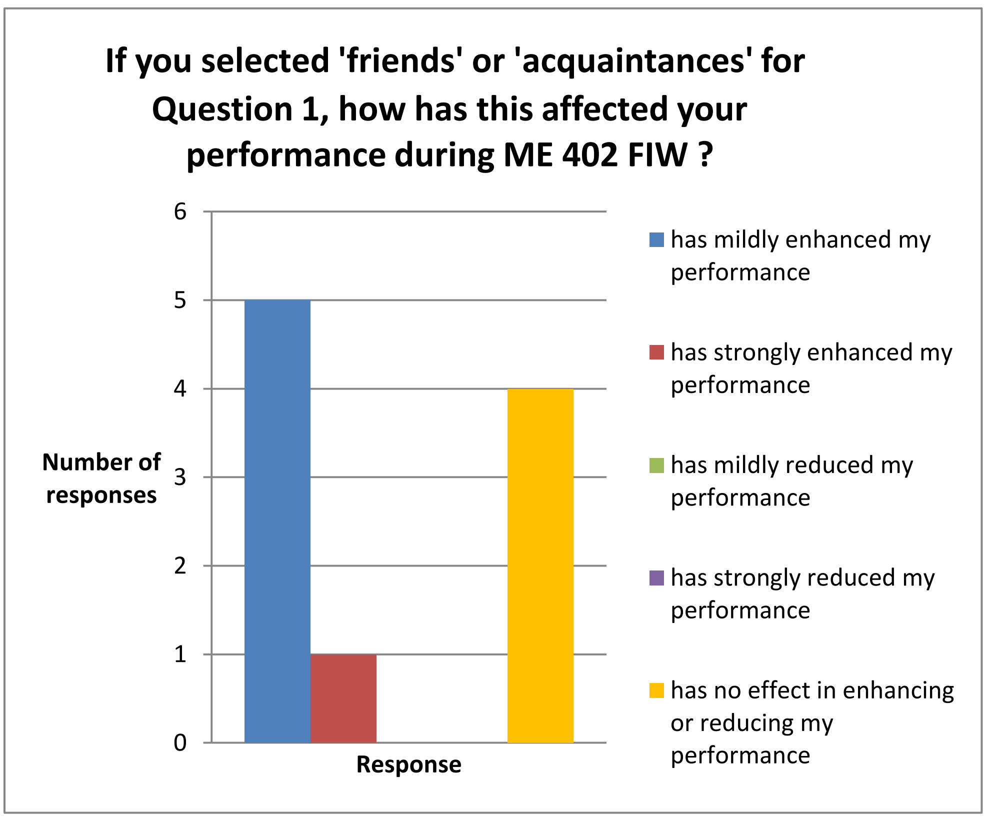


Figure 6.7: Response to Question 3

Question 4: In which of the following areas do you think your performance was affected (enhanced or reduced)? Select all that are applicable.

Table 6.5: Percentage response to Question 4

Question 4 Percentage Response	
Expression of disagreement	19%
Expression of ideas	31%
Fear of judgment	19%
Division of responsibilities	31%

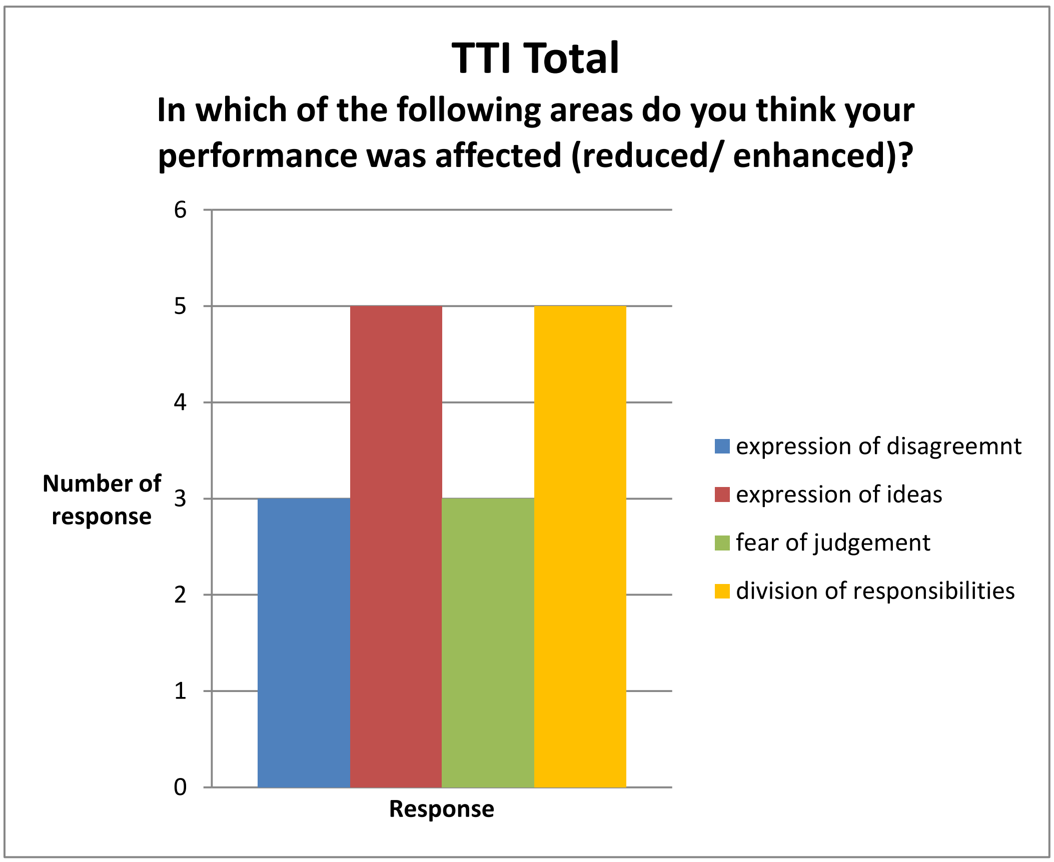


Figure 6.8: Response to Question 4

Question 5: Do you have prior experience working with one or more members from current project in any other team project?

Table 6.6: Percentage response to Question 5

Question 5 Percentage Response	
Yes	91%
No	9%

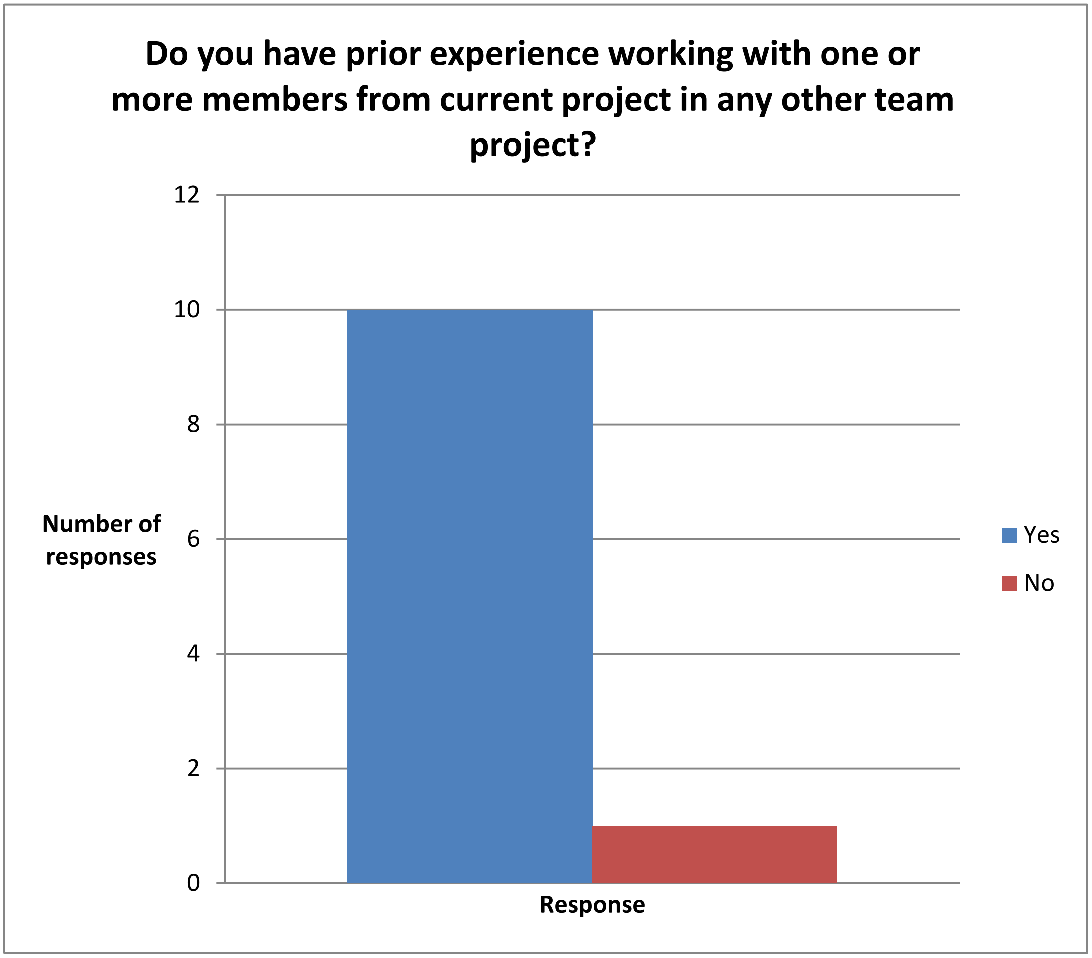


Figure 6.9: Response to Question 5

Question 6: Do you have prior experience working in a team project? Choose only one.

Table 6.7: Percentage response to Question 6

Question 6 Percentage Response	
Yes	100%
No	0%

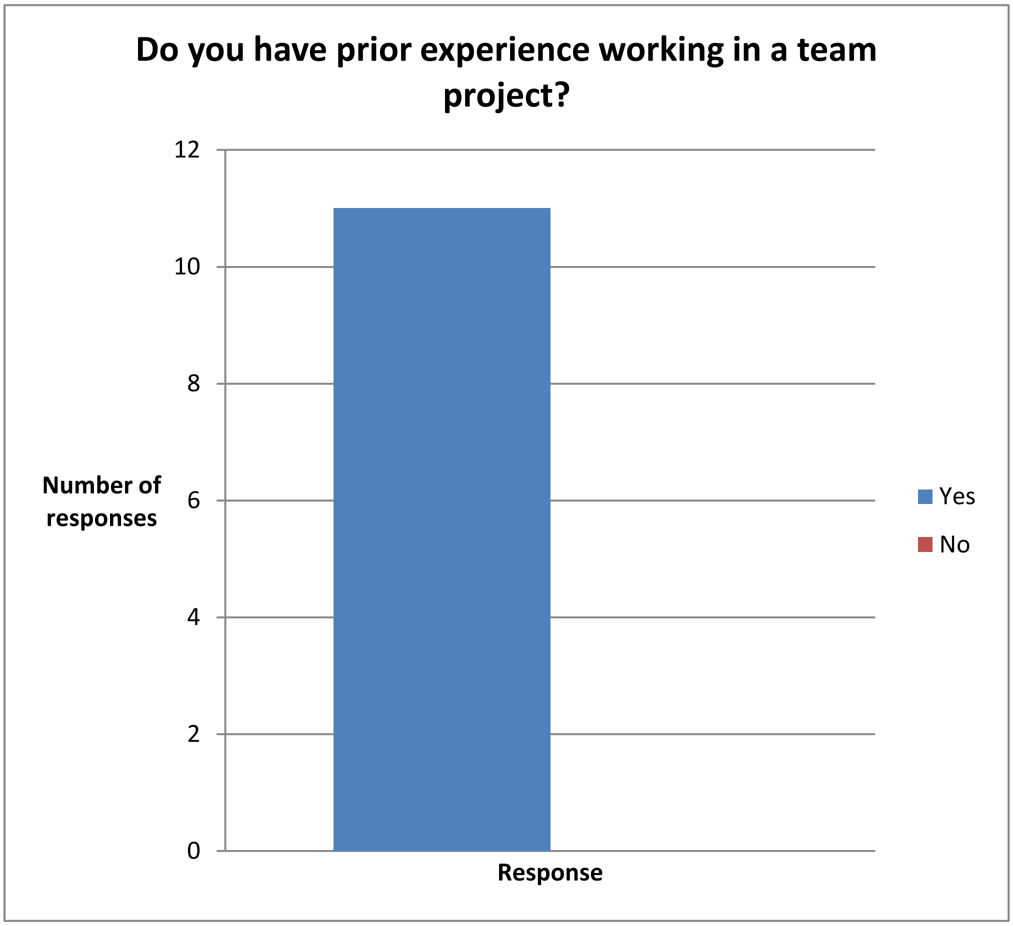


Figure 6.10: Response to Question 6

Question 7: The facilitated hybrid ideation workshop is an effective technique for generating conceptual design ideas for ME 402 project? Choose only one.

Table 6.8: Percentage response to Question 7

Question 7 Percentage Response	
Strongly disagree	0%
Disagree	9%
Neutral	9%
Agree	82%
Strongly agree	0%

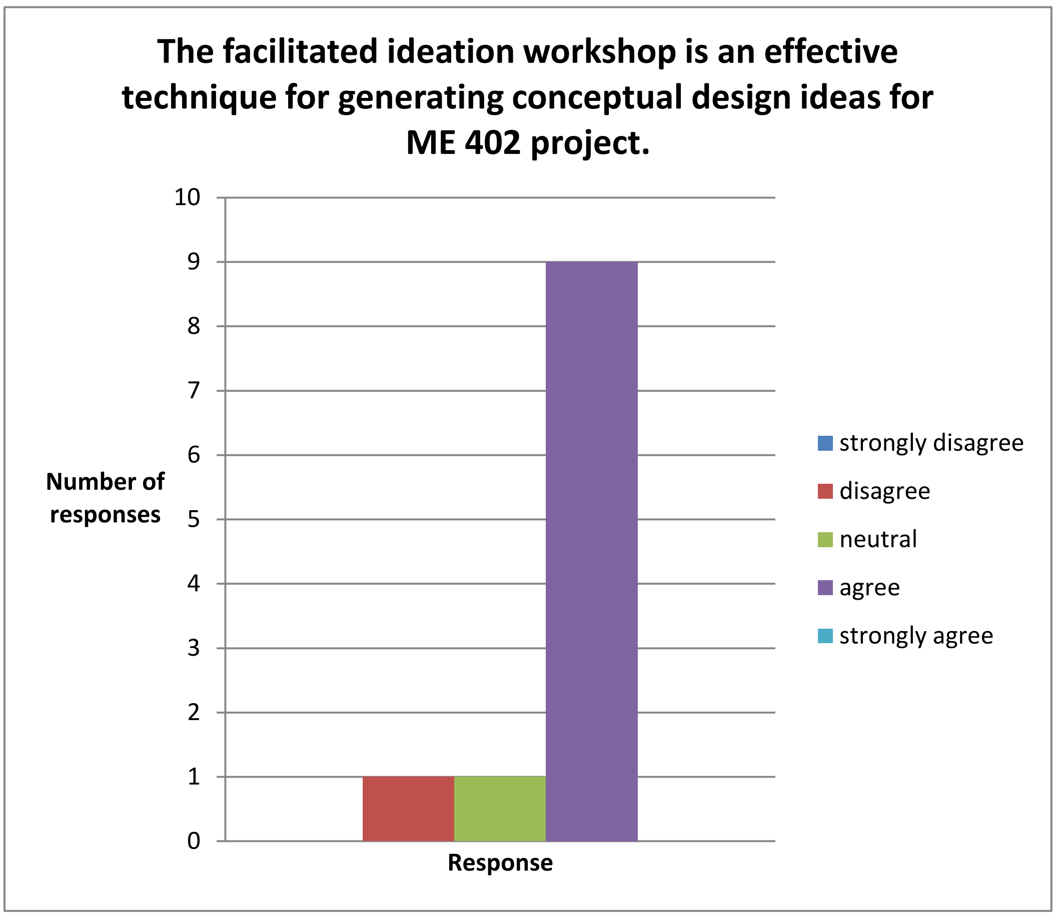


Figure 6.11: Response to Question 7

Question 8: Did you build on / iterate on each other's ideas during the facilitated hybrid ideation workshop? Choose only one.

Table 6.9: Percentage response to Question 8

Question 8 Percentage Response	
Yes	73%
No	27%

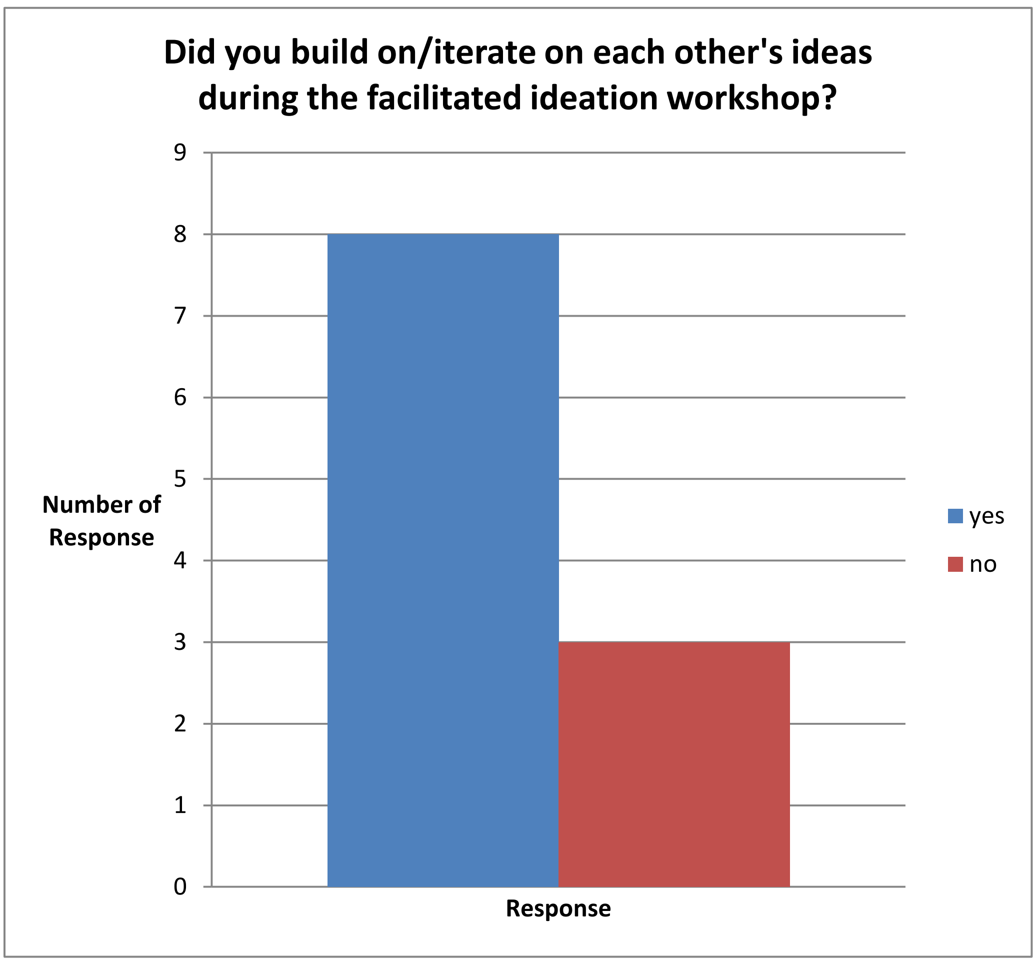


Figure 6.12: Response to Question 8

Question 9: Building/ iterating on each other's ideas is an effective way to improve the quality of ideas generated during the workshop. Choose only one.

Table 6.10: Percentage response to Question 9

Question 9 Percentage Response	
Strongly disagree	18%
Disagree	0%
Neutral	0%
Agree	64%
Strongly agree	18%

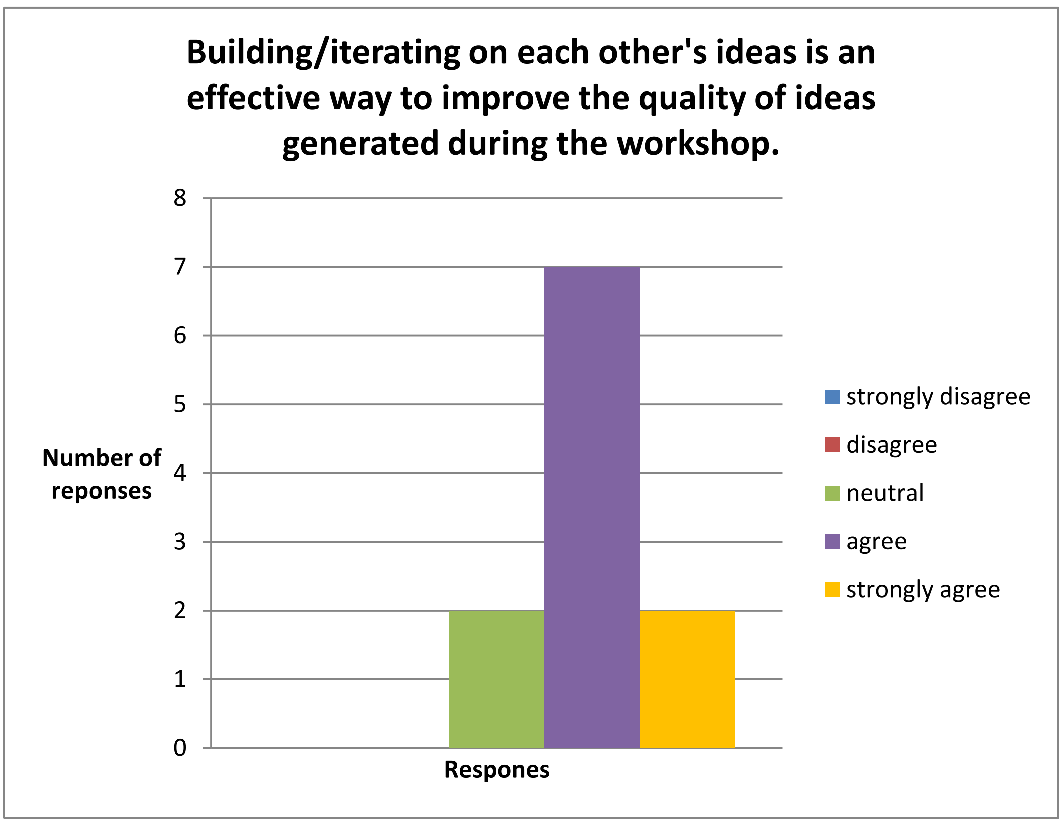


Figure 6.13: Response to Question 9

Question 10: The time provided for the facilitated hybrid ideation workshop per session is sufficient. Choose only one.

Table 6.11: Percentage response to Question 10

Question 10 Percentage Response	
Strongly disagree	18%
Disagree	0%
Neutral	9%
Agree	73%
Strongly agree	0%

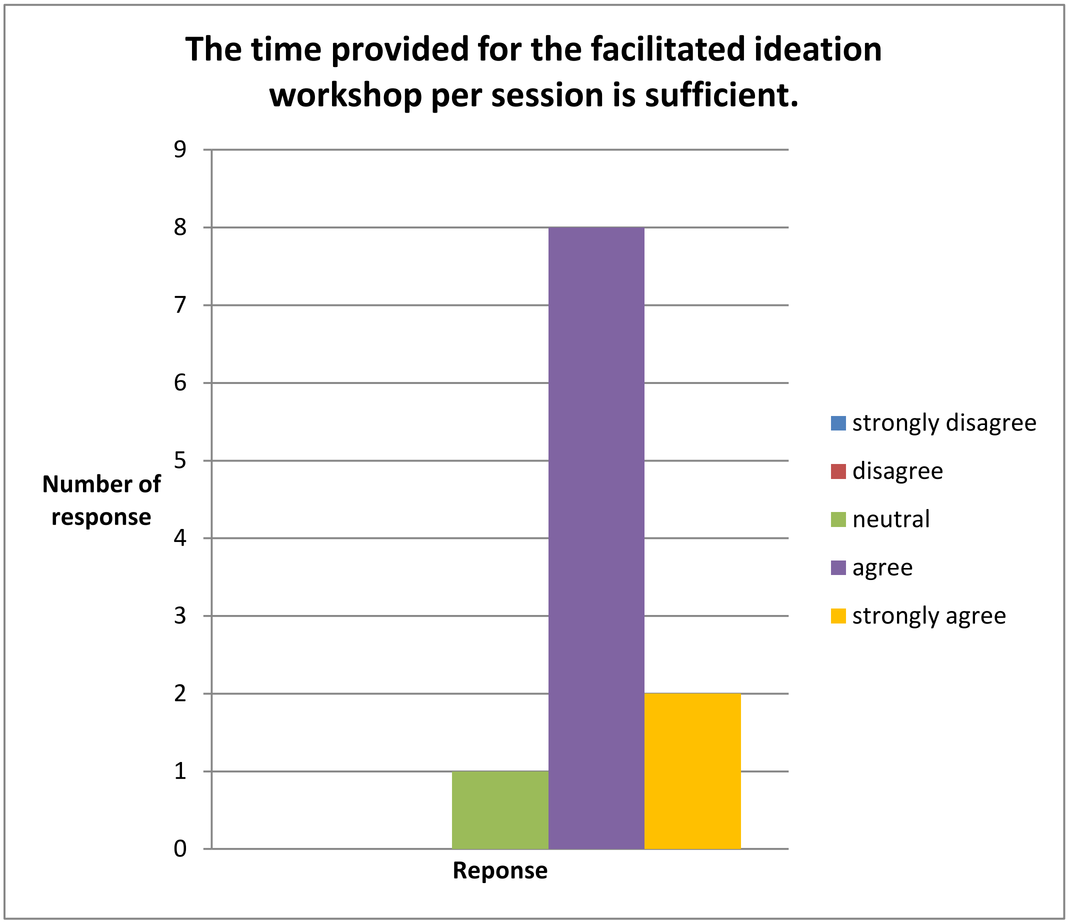


Figure 6.14: Response to Question 10

Question 11: Which of the following features of the facilitated hybrid ideation workshop ideation significantly improved your performance? Select all that are applicable.

Table 6.12: Percentage response to Question 11

Question 11 Percentage Response	
Intervention of the facilitator to resolve conflicts between team members	2%
Allowing sufficient time for individuals to ideate and explain ideas	6%
Flexible timings of the facilitated hybrid ideation workshop	14%
Following an individual to group approach for ideation and discussion on ideas	19%
Formulating objectives for next meeting and presentation	19%
Finding research material and sources to stimulate idea generation	8%
Feedback on weekly ME 402 presentation	16%
Assisting group to focus on project objectives and help meet them on time	14%
Did not find the facilitated hybrid ideation useful	2%

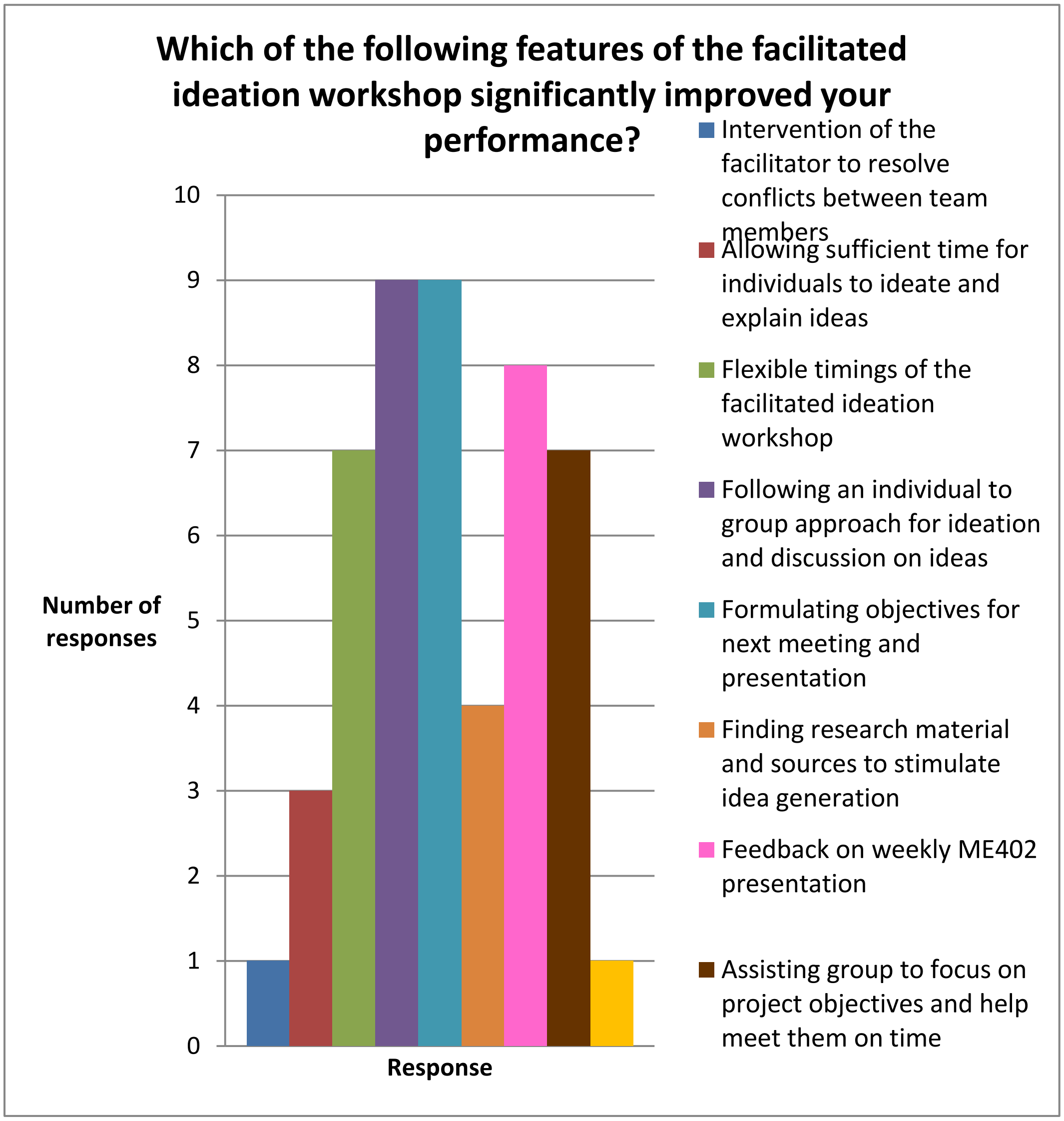


Figure 6.15: Response to Question 11

Question 12: Building/ iterating on each other's ideas increased your creativity. Choose only one.

Table 6.13: Percentage response to Question 12

Question 12 Percentage response	
Strongly disagree	0%

Question 12 Percentage response	
Disagree	0%
Neutral	27%
Agree	64%
Strongly agree	9%

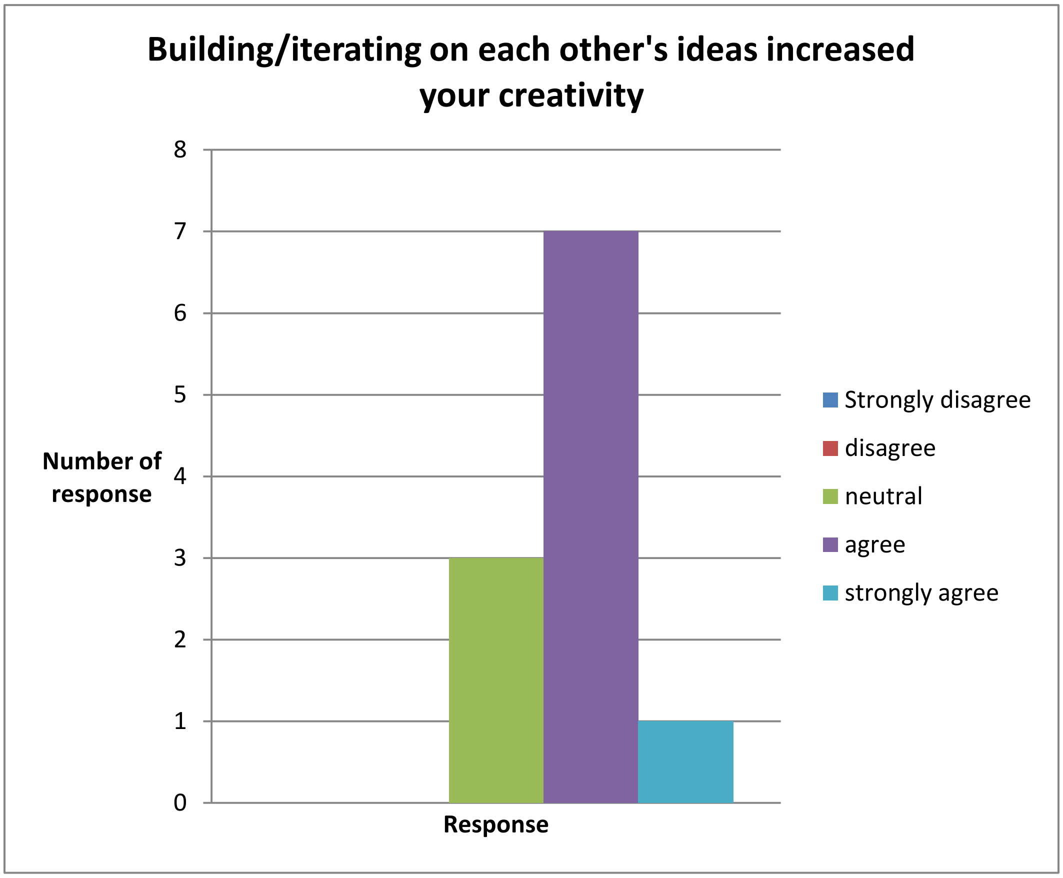


Figure 6.16: Response to Question 12

Question 13: The facilitated hybrid ideation workshop challenged you to generate creative and unique ideas as an individual. Choose only one.

Table 6.14: Percentage response to Question 13

Question 13 Percentage Response	
Strongly disagree	0%
Disagree	9%
Neutral	18%
Agree	64%
Strongly agree	9%

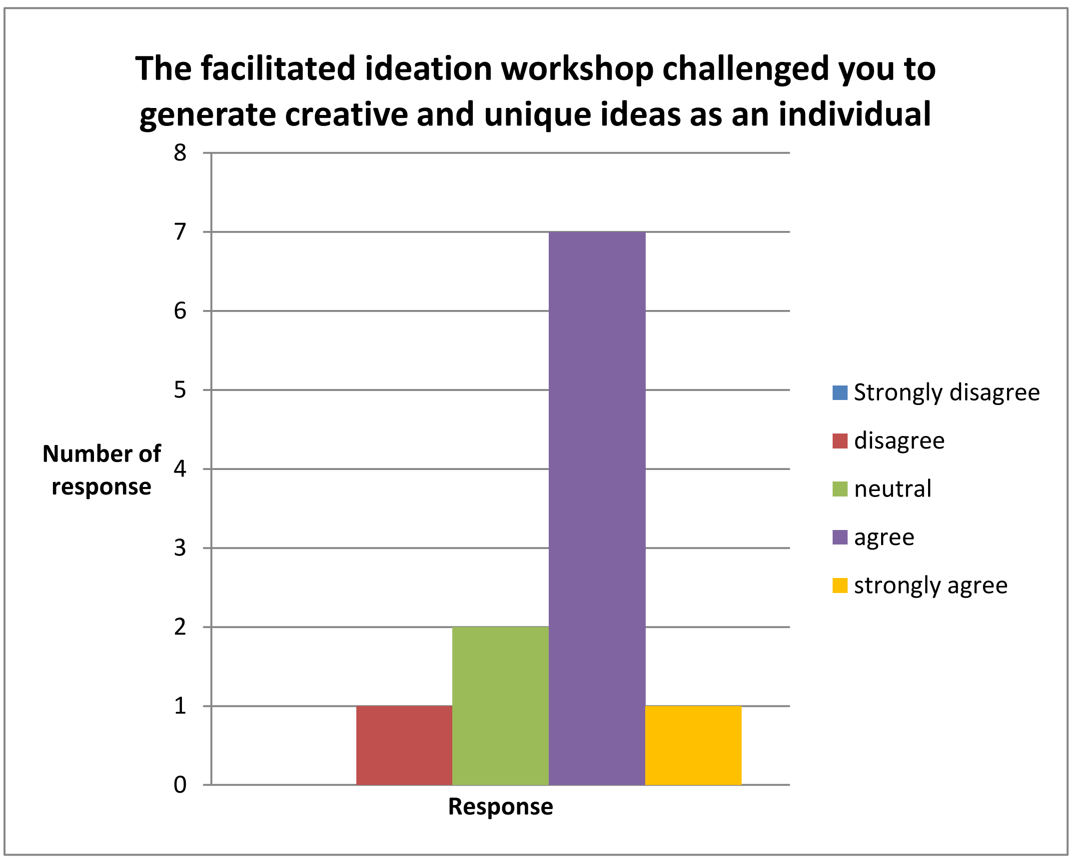


Figure 6.17: Response to Question 13

Question 14: During the facilitated hybrid ideation workshop, the process of first generating ideas individually followed by group discussion and rating is effective for eliminating bad ideas and increase the overall quality of ideas as a group. Choose only one.

Table 6.15: Percentage response to Question 14

Question 14 Percentage Response	
Strongly disagree	40%
Disagree	0%
Neutral	0%
Agree	40%
Strongly agree	20%

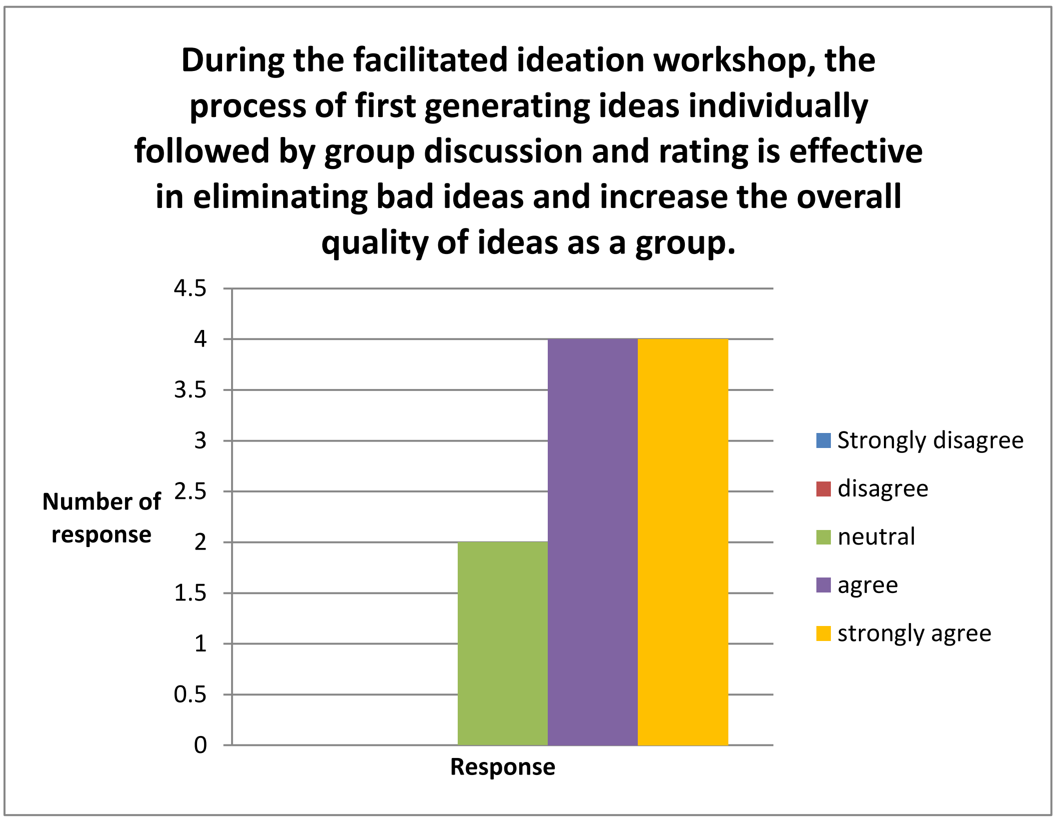


Figure 6.18: Response to Question 14

Question 15: The facilitated hybrid ideation workshop improved the performance of your team to function better collectively and develop increased quality ideas. Choose only one.

Table 6.16: Percentage response to Question 15

Question 15 Percentage Response	
Strongly disagree	0%
Disagree	0%
Neutral	18%
Agree	64%
Strongly agree	18%

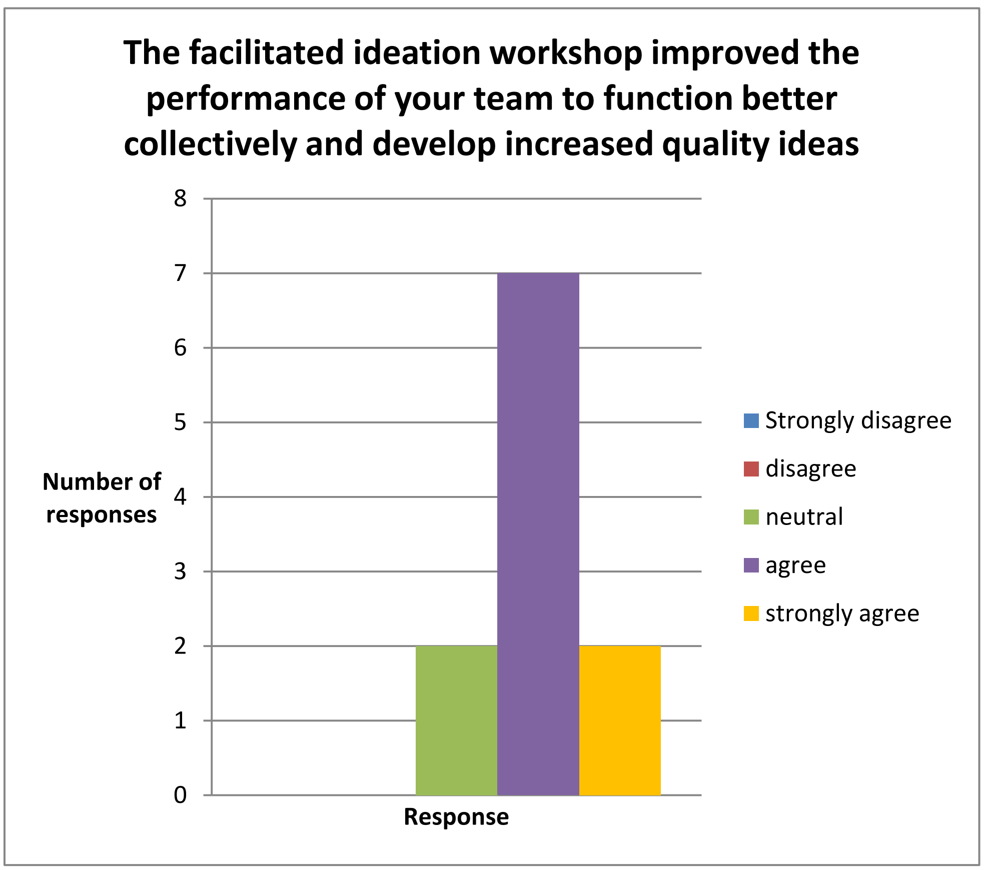


Figure 6.19: Response to Question 15

In addition to the above questions, the students were also required to provide additional feedback and comments to improve the facilitated hybrid ideation workshops in future. Some of the participants answered this question and provided the following feedback:

- Research material for stimulating ideas have helped a lot
- Likes the setup, forces groups to focus and help set deadlines and objectives
- Help stay on time and improve presentations
- Workshop could be less directive or structured so that teams can bring up what they think are biggest challenges
- Great opportunity to breakdown ideas, could eliminate the number of meetings, not as productive as I liked during last few meetings
- Didn't feel like being pushed towards building off each other's ideas which could have been helpful has it been done.
- Research directives was biggest asset, more detail level discussion would be helpful
- Providing agenda for next meeting to students to come prepared was productive

Based on other descriptive survey questions, the following responses have been procured regarding the participants past experience working in a team project. Due to the descriptive nature of the responses, certain keywords which appeared most frequently have been used to filter responses and draw conclusions.

Question A: Please provide additional information regarding the past team project you worked on.

Table 6.17: Percentage response for Question A

Percentage Response	
ME 401	50%
Other	50%

Question B: Number of team members in your past team project.

Table 6.18: Percentage response for Question B

Percentage Response	
Four	90%
Three	10%

Question C: Describe your overall experience during the project.

Table 6.19: Percentage response for Question C

Percentage Response	
Good experience	66.67%
Bad experience	33.33%

Question D: Did you follow any particular technique to generate ideas for the project? If yes, please provide a brief description.

Table 6.20: Percentage response for Question D

Response	No of responses	Percentage Response
No technique followed	6	42.85%
Brainstorming	3	21.42%
Functional Decomposition	2	33.33%
Morphological chart	2	33.33%
Reverse Engineering	1	16.67%

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