ANALYSING THE EFFECTS OF INCENTIVES AND MODEL ATTRIBUTES ON CAD MODEL CREATION AND ALTERATION

A Thesis

by

RAM PRASAD DIWAKARAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2010

Major Subject: Mechanical Engineering

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Approved by:

Co-Chairs of Committee,	Michael Johnson
	Julie Linsey
Committee Member,	Christian Schwartz
Head of Department,	Dennis O'Neal

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ABSTRACT

Analyzing the Effects of Incentives and Model Attributes on CAD Model Creation and Alteration. (December 2010)

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Co-Chairs of Advisory Committee: Dr. Michael Johnson
Dr. Julie Linsey

Modern computer-aided design (CAD) systems have contributed significantly towards product development cycle time reduction and product quality improvement. To enhance the performance of CAD systems engineers must be able to create CAD models of conceptual designs quickly; at the same time CAD models must be easy to alter, so as to accommodate the rapid changes that the design undergoes through the lifecycle. However, there is no agreement in the way CAD models should be created to accomplish these goals. This work attempts to assess the effects of incentives on CAD model attributes during model creation and alteration; the effects of CAD model attributes on alteration are also investigated. Its aim is to derive prescriptions based on empirical evidence to improve CAD model creation and alteration efficiency.

The CAD models under study are created by three sets of participants – students from a junior level CAD course, students from a senior level CAD course and experienced engineers involved in product development activities. The participants are incentivized to create and alter CAD models of designs they are provided with. The results indicate that upon removal of incentives, engineers (both students and professionals) tend to compromise on proper modeling procedures. Experts are quicker and adhere to commonly agreed correct modeling procedures during CAD model creation and alteration than students. The results also indicate that it is beneficial for alteration to construct a model with several simple features as opposed to a few complex features and that these features be fully constrained. Maintaining the traditional feature sequence improves the perception of the model. The retention and alteration of features (as opposed to deletion) is also shown to be positively correlated with model perception ratings.

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TABLE OF CONTENTS

LIST OF FIGURES

FIGURE Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

Computer aided design (CAD) systems are one of the most popular tools used in the product development process [1]. To appreciate the impact CAD systems have had on the product development process, it is important for us to understand how the current, concurrent engineering (CE) process has evolved from the traditional approach. The traditional product development process was highly serial. The various departments involved (Figure 1) in the process acted independent of each other and exchanged only the results of their work with the other departments. The process was sequential because a department did not start working until it received inputs from its preceding department [2]. Once the design was completed and verified, it was "tossed over the wall" to the manufacturing department for review of manufacturability, testability and serviceability.

The design team was then notified of the changes suggested by the manufacturing department. Following this the design would be reworked and the necessary changes incorporated. This was a highly iterative process. The flow of information in this process was slow because information flowed only in one direction at any given time [3]. Further, design defects identified during the production phase called for modification of the design and/or manufacturing processes. Product quality was often

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This thesis follows the style of Journal of Computer-Aided Design.

compromised to avoid further delay. Thus the traditional process had a long lead time to market, high cost and poor quality products as output [4]. The approach was reactive rather than proactive. Defects were detected during the manufacturing or production phase and the design was reworked rather than identifying them during the design phase and preventing them from occurring in the later stages. To survive today's competitive market, industries ought to adopt processes that are cost effective, that help introduce their new products with shorter lead time and with better quality.

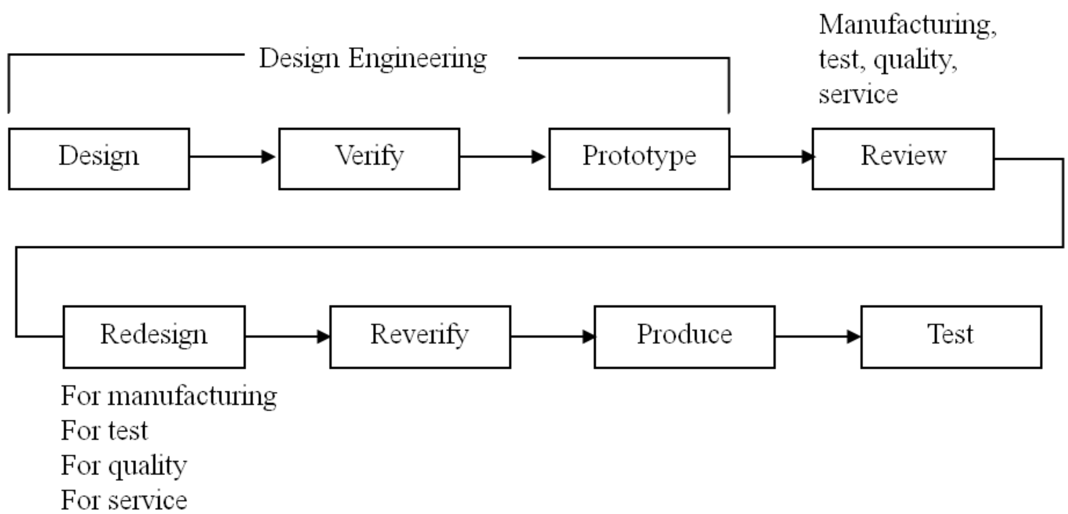

Figure 1 – Flowchart of the traditional product development process [2]

A study by Huthwaite revealed that of the entire product development costs, only about 5% was spent on designing the product. Yet about 80% of the product development activities were influenced by the product's design [5]. Given the impact the design phase had on the developmental process, Boothroyd suggested that investing additional time in the design stage could help reduce the overall developmental costs and time to market [6]. This paved way for the CE approach to product development. The fundamental principle of CE is that the downstream concerns of product development are to be addressed in the early stages of design [7]. Several functional departments actively participate in and contribute to the design of the product (Figure 2). Various aspects of the product including manufacturability, testability, safety and serviceability are considered during the design phase. The process helps identify major cost and quality issues in the design stages where the cost of making changes is minimal. It also ensures that the likelihood of hard-to-solve problems surfacing during late stage reviews is minimal [8, 9].

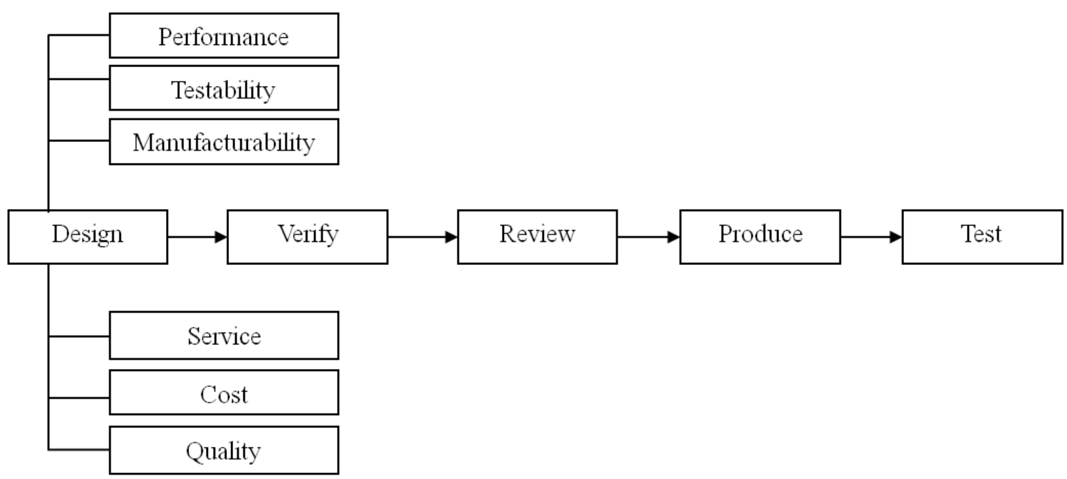

Figure 2 – Flowchart of the concurrent engineering process [2]

The goal of the CE process is to address the shortcomings of the traditional product development process. The adoption of CE methodology reduces development lead time, overall development costs and improve quality of the product [8, 10]. Koufteros, et al. reported that the total effect of CE not only improved product quality but contributed towards product innovation [11]. In one of the projects at General Electric, under the Defense Advanced Research Projects Agency (DARPA) initiative, the product development team members were able to seamlessly share, access and store up-to-date information. The testing portion of an airfoil development project was reduced to seven months from 18 months [12]. A list of the benefits to the various stages of product development is given in Table 1 [13].

Table 1– Benefits of Concurrent Engineering [13]

Development time	30-50% less
Engineering changes	60-95% less
Scrap and rework	75% reduction
Defects	30-85% fewer
Time to market	20-90% less
Field failure rate	60% less
Service life	100% increase
Overall quality	100-600% higher
White-collar productivity	20-110% higher
Return on assets	20-120% higher

Given that following the CE methodology is beneficial to the product development activities in several ways, the tools that help in the implementation of CE are of prime importance. Dubensky listed a set of techniques, both computer based and non-computer based, for the successful implementation of CE. Of these, the computer based techniques included CAD, geometric modeling, analysis and simulation modeling [14]. CAD systems are engineering tools that help speed up the new product development process by assisting in the conception, alteration, validation and optimization of design [15, 16]. CAD systems help accelerate the product development cycle by making a concurrent engineering approach possible on digital networks [17]. According to Kao and Lin the full potential of CE cannot be realized without CAD [18].

Companies initially invested in CAD systems since they would render the design process paperless by storing the databases electronically and would automate the routine design tasks; in the nascent stages, they were considered just as electronic drafting boards [19]. Later, the demand to improve the product development performance (product development cycle time, development cost and quality) drove the usage of CAD to integrate the functions of engineering and manufacturing [20].

CAD technology enables the graphical and mathematical simulation of a product's systems and components [16]. Often, several teams (even from different geographical locations) work on subsystems with manageable complexity levels that make up a product. These teams are bound by the functional interfaces of the product [21]. The design engineers first create a design as a solid model using a CAD tool [4]. The 3D visualization of the product helps engineers gain a multi-functional perspective of the product. It has been found to be helpful in ascertaining the manufacturability of the part [22]. With CAD, the real prototypes which were expensive and time intensive could be replaced by digitally pre-assembled parts. This also allowed engineers to visualize how the part or sub-assembly fit into a larger system; this was of great help especially when the system comprised components from several functional groups [23].

When implemented well, the CAD databases could be made concurrently available to multi-disciplinary teams [24] and simulations models including structural and vibrational finite element analysis (FEA), computational fluid dynamics (CFD) simulations, tolerance analyses, kinematics (motion analysis) simulation and computer-aided manufacturing (CAM) simulations could be developed [4]. The success of CE depends on these different groups sharing the same knowledge about the product [23]. Carrying out both design and simulation activities results in the engineers viewing the design from wider perspectives [4].

With the above mentioned capabilities, CAD systems facilitate communication between engineers from different functional groups like design, analysis simulations, manufacturing and testing [23]. The results obtained from the simulations could be reviewed by cross-functional teams and a trade-off study could be conducted to improve the design thus minimizing the design iterations. The product could then be rapid-prototyped for design verification purposes. The necessary changes could then be incorporated into the design with minimal cost [4]. CAD systems offer the capability to recall the designs and make these changes or improvements to them [19]. Da Silveira, et al. cite that CAD, with its ability to quickly modify designs, is one of the key technologies enabling mass customization strategies [25].

CAD databases central to several teams are managed by product lifecycle management (PLM) systems which provide engineers with controlled access to the CAD databases [26]. PLM systems are used throughout industry and assist in facilitating global development projects [27]. When used in concert, CAD and PLM systems are powerful tools for enhancing product development performance. However, to fully harness the power of these tools requires that they be populated with designs that others can easily understand and change.

Prior to the introduction of CAD, prototyping activities could not be started off until all the drawings reached a certain level of completion. CAD tools now have the capability to transfer numerical control (NC) data seamlessly to CAM tools enabling easy integration into a computer-aided engineering (CAE) model [23]. The possibility of seamless transfer of information from CAD to CAM tools eliminates misinterpretation of the design in addition to eliminating the need for hard-copy drawings [16]. Today, CAD systems are even coupled with administrative systems for scheduling, planning and tracking paving way for a computer integrated manufacturing (CIM) environment [28].

Chang, et al. had proposed a concurrent design and manufacturing (CDM) approach (Figure 3) with the CAD model at the center of the entire product development process [4]. The impact of using CAD databases is felt throughout the development process. In order to take full advantage of CAD systems, companies should thoroughly understand what the systems can offer. Companies must also modify their working culture in a way that they leverage the systems' capabilities [29]. CAD systems help improve various aspects of the product development process. In some companies, the quality of the products developed has increased with the efficient use of CAD systems [30]. Other companies have demonstrated the ability to reduce new product development costs by using CAD systems [31]. CAD systems have helped design engineers assess multiple design options prior to a final design being chosen. Since many designs are assessed and analyzed, engineers produce high quality, optimized design solutions which often do not have manufacturability issues [31]. However, when poorly implemented, CAD systems can inhibit communication and cause development problems [32].

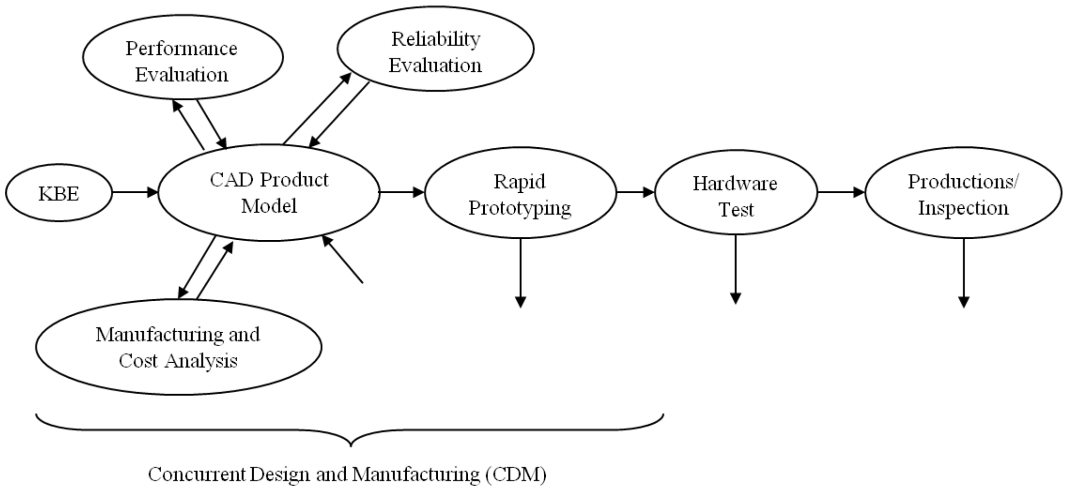

Figure 3 – The concurrent design and manufacturing (CDM) process [4]

In one example, the introduction of CAD/CAM systems (Computervision and CADDstation) reduced development times from over nine months to five months [33]. Another example demonstrating the implementation of CAD was the development of Boeing 777 – a joint venture between Boeing and five Japanese aircraft manufacturers. The design changes were reduced by 75% - both design improvements and changes due to errors were minimized. The number of engineering hours, the number of prototypes and the number of mockups were all reduced as well [23].

CAD systems aid in digital 3D modeling, digital pre-assembly, supporting simulation analyses, facilitating communication between teams and integration with process planning and manufacturing. With the advantages CAD systems have imparted to the product development process, they are seen as a means of alleviating the time pressures of the modern development process [20]. However, it is also possible that these time pressures are leading designers to use CAD tools improperly; they tend to compromise on proper modeling procedures; this in turn might affect the alterability of the model.

The goal of this thesis is to assess the effect of incentives on 3D model attributes during creation and alteration. Models created by both students and professional CAD users are studied and compared. Based on the findings useful prescriptions for efficient 3D model creation and alteration are suggested. The thesis is organized into three separate studies – each one conducted on a different set of users. The literature review is presented in Chapter II. The research methodology is described in Chapter III. The results of the exercises carried out with Pro|Engineer student users, Solidworks student users and Pro|Engineer professional users are presented in Chapter IV, Chapter V and Chapter VI respectively. A discussion of the results of the exercises and how they compare follows in Chapter VII. The limitations of this work and future work are detailed in Chapter VIII.

CHAPTER II

BACKGROUND

2.1. Model Creation and Alteration

Reducing the product development cycle time is crucial to the growth of a company; development lead time is one of the key metrics used to measure the development cycle performance [34]. The introduction of CAD systems has helped automate routine design activities [19]. With the CAD systems replacing manual drafters, improvement in the product development performance has been demonstrated [35]. However, design engineers are required to upgrade their skill levels by mastering the CAD systems apart from regular design activities [36, 37]. While improvement in productivity over the manual drafting process has been demonstrated [35], further improvement in performance demands engineers to identify more efficient methods for the creation and alteration of 3D CAD models.

According to Lee, modern solid modeling systems have five major components – sketch, solid modeling, parametric engine, feature manager and assembly manager. These components are used in several possible combinations to create 3D CAD models [38]. Hartman found that experts considered feature order, parent/child relations, sketched geometry, sketching plane and model orientation to create a model [39]. However, researchers do not agree on one efficient way to create 3D models. Rynne and Gaughran suggest the use of simple sketch geometry for efficient model creation; however they provide no empirical evidence for their prescription [40]. Hamade, et al. recommend that for efficiency engineers must use a minimum number of features to create a 3D model [41]. Bhavani, et al. also claim that experts use fewer features that are more complex to achieve their goals sooner as compared to novices [42]. On the other hand, Chester reports that an expert's strategy for model creation would be based on how easy it would be to make changes to it later on [43].

In a product development environment, there are several factors that influence the design of a product. Each product development phase inflicts dynamic changes upon the design. The initial design undergoes several modifications before converging to a final design and the CAD model gets dynamically updated too. CAD models also need modifications when they are used for finite element simulations – a model with fewer surfaces would reduce the complexity of the finite element mesh; certain features of the part which would not affect the results of the analysis are deleted or suppressed from the CAD models. According to Lee logical regions called constructions can be used to subdivide complex models. When the model is built in levels of constructions, modifying one of the constructions will affect only that construction locally. Hence Lee recommends that by building complex models using multi-level constructions, the editing time can be greatly minimized [38]. CAD models of variants of a product are generally modifications of the CAD models of the previous versions. It is very common in the industry to make minor modifications to already engineered parts or sub-systems of a product for use in a new product. According to Clausing, a product's success depends on an optimal mix of innovation and reuse. Reuse will prevent excessive, empty innovation that the market does not require [44]. Thus, modification of a CAD model is as important to the product development process as is creation. A survey of over 150 engineers and CAD trainers by Salehi and McMahon indicated that it was difficult to find parameters and relations and was also difficult to make changes to a CAD model created by another engineer [45]. Thus the alterability of a CAD model has to be borne in mind during creation. While alterability of a CAD model is of critical importance, capturing the rationale behind the design during CAD model creation strongly influences the alterability of the model [45].

2.2. Design Intent

There are several ways to define the intent of a design. Design intent can broadly be defined as the purpose or rationale behind the choice of a given object [46, 47]. Conklin and Yakemovic define design intent as the path determined by the decisions and alternatives chosen through the evolution of the design, joining the initial and the final states of the design [48]. Iyer and Mills define design intent as [46]:

> *the insight into the design variables (design objectives, constraints, alternatives, evolution, guidelines, manufacturing instructions and standards) implicit in the structural, semantic and practical relationships between the geometric, material, dimensional and textual entities present in the CAD representation*.

For the purpose of this work, design intent is defined as the rationale behind each feature contained in a CAD model including the constraints imposed on them, the parameters that define them, their order, and the decisions leading to the choice and organization of these features, constraints, and parameters to represent geometry with a given function. Proper design intent is defined as that which conveys the function of the geometry in a robust (where alterations produce intuitive responses) manner.

Given that there are numerous ways to model a component with modern CAD tools, the design intent of a CAD model should be directly related to the functions of the modeled component and allow for it to be easily changed and still perform those functions [49-51]. Design intent is at the core of the CAD modeling process, encompassing feature selection, order, and organization [49]. According to Rodriguez if the capture of design intent is undermined while creating a CAD model, serious problems might arise later on. The model might reach a critical stage where further parametric modification would become impossible and would result in the failure of the part. Thus, capturing design intent while creating a 3D model is of prime importance [52]. Modern commercial feature-based, parametric CAD tools offer the capabilities to capture the rationale behind a design.

2.3. Feature-Based Design and Parametric Design

Today's CAD systems help the engineers create feature-based 3D solid models. Some of the definitions for a feature include:

- A feature is a primitive (geometric form or entity) which eases the designing process [53]
- "the generic shapes or characteristics of a product with which engineers can associate certain attributes and knowledge useful for reasoning about that product" [54]

Further, features can be classified broadly into design and manufacturing features. Design features "are a set of geometric elements that carry certain significance in production functionality" [55]; "they are shape elements serving certain functions"

[56]. For instance, ribs are features that strengthen walls and pin connections allow restricted movement [56]. The ‘extrude’ and ‘cut’ features are primitive design features in CAD tools. Feature based design is the construction of CAD models using such design features as building blocks. Depending on the software, they include basic elements (e.g., blocks, bosses, pockets, or holes) or sketch manipulations (e.g., extrusions, revolves, or blends). This flexibility of sketch based feature creation introduces the possibility of a part to be created in several different ways. The same part with a large number of features created with simple sketches can also be created with fewer, more complex sketched features.

In contrast, manufacturing features are features that would result from machining. For example, holes that are drilled and slots/pockets that are milled are manufacturing features [56]. In subsequent discussions throughout this work, the term feature will refer to a design feature. One of the main goals of feature based design, in addition to the representation of the shape/geometry of the design, is to provide information for manufacturing and capture design intent [57]. Singh and Jebaraj claim that design intent can be captured and transferred to downstream activities through the feature based design approach [58].

Parametric design is the use of parameters for the definition of a form. The shape of a solid model is a function of a set of parameters and constraints. The various steps involved in creating a model are captured using these parameters [43, 59]. For example, a block is defined by its length, breadth and height and its location in the global coordinate system. A hole in the block is defined by its location with respect to the global coordinate system and its depth into the block. The parameters are related to the features and help in easy creation and modification of the same. Parameterized models also inherently have the ability to capture the rationale behind a design [60]. Feature based modeling systems allow the designer's intent to be easily expressed by manipulating the features directly [61].

2.4. Expertise

Since one set of subjects participating in the study are experts, it is important to understand the qualities of experts. This would also help identify the differences between novices and experts as applicable to CAD modeling. It is their ability to store and retrieve large "chunks" of data pertaining to their own domain which makes experts stand out [62]. They have a strong qualitative understanding of the subject gained through experience and are able to analyze problems at hand in depth. They have better short and long term memories associated with mental models in their domains. These qualities help them perform tasks quickly and with fewer mistakes when compared to the same tasks performed by novices [63]. There is a search associated with every task – the search for the best path to be picked from several alternatives to reach the goal. With expertise, the search becomes very narrow and selective and the chosen path is likely to lead to quick and successful completion of the task. Novices on the contrary follow a trial and error methodology to pick their path – some of these paths might not even be able to take the task to completion [64, 65].

Scientists have tried to understand the reason behind expertise and how experts are able to perform better. Skilled CAD system users are said to have the ability to recognize several features including symmetry and repetition by virtue of their experience with CAD models [66]. Bhavani and Garrett demonstrated with a pilot study that it is procedural knowledge which helps experts perform better [42]. Bonner, et al. claim that practice is essential for acquiring procedural knowledge and this acquisition is independent of any form of prior formal training [67]. Lang, et al. studied the significance of procedural knowledge acquisition and demonstrated the performance difference between expert and novice CAD users. A domain expert was able to transfer their procedural knowledge to a different CAD system. Also, by using a better strategy to create a model, a system expert was able to considerably improve their efficiency [68]. However, new information has to enter as declarative knowledge and must be complied through practice before the development of procedural knowledge [65]. To sum up, while procedural knowledge is what differentiates the experts from novices, one has to gain declarative knowledge and accumulate procedural knowledge to become an expert.

2.5. Procedural and Declarative Knowledge

The knowledge that one should possess to perform a skilled task can be divided into declarative knowledge and procedural knowledge. A very generic definition of declarative or the “know-what” knowledge will be the knowledge of the facts of the world. From a CAD stand point, the declarative knowledge a user must possess to create a 3D model is the set of commands that is specific to that CAD system [67, 69]. On the other hand, knowledge of the various methods, strategies or steps to complete a task constitutes procedural, “know-how” or strategic knowledge [43, 69]. In the context of

CAD, it is the knowledge of the various combinations of features (sets of a few complex sketched features or several simple features) that could result in the same 3D model. It should be noted that declarative knowledge is system specific while procedural knowledge is generic knowledge which once acquired can be applied across systems [41, 70]. Both declarative and procedural knowledge components play vital roles in the development of expertise. Anderson claims that declarative knowledge must be in place for procedural knowledge acquisition to be possible [65]. In an industrial setting, while engineers gain experience and expertise they are also constantly exposed to project specific incentives to keep them motivated.

2.6. Incentives

Incentives do not always help enhance performance. The effect of incentives depends on the task being performed and the magnitude of the incentive. Camerer and Hogarth reviewed several experiments with varying levels of performance-based incentives. The study revealed that there was no clear effect of incentives on performance. Incentives had no effect on the performance of tasks involving judgment and decision-making. But incentives helped reduce the variance in performance. When additional effort was demanded for a very low reward, incentives appeared to lose their impact [71]. Jenkins, et al. claim that in an experimental setting, incentives tend to improve the quantitative performance but not the quality [72]. In an industrial setting, CAD systems are expected to help engineers against the time pressures of the product development process [20]. At the same time it is also possible that such time pressures (created by incentives and deadlines) lead designers to compromise on proper modeling techniques.

CAD systems have been shown to be instrumental in helping industries realizing the full potential of CE [18]. CAD models are also central to the entire product development process assisting in several downstream activities [4]. Hence, CAD model creation and alteration efficiencies become critical to the development process. However, researchers do not agree on one particular way of model creation. Reducing the number of features has been shown to reduce required design time [41]. Design experts differ on the number of features to include when modeling a given part (even under time pressure) [39]. Rynne and Gaughran provide no empirical evidence for their prescriptions for model creation [40]. The work of Hamade, et al. was based only on the creation of CAD models [41].

While there has not been any consensus on the ways of CAD model creation there have been few studies analyzing ways of alteration of CAD models or how CAD model creation affects alteration. Incentives in the industry urge engineers to create and alter CAD models quickly. But the effect incentives have on CAD model attributes during model creation or alteration are yet to be studied. While there have been a few studies demonstrating the ability of experts in transferring their knowledge between different CAD systems [73], there has not been a significant quantitative study on the way experts create or alter CAD models.

The goal of this work is to assess the effect of incentives on CAD model creation and how CAD model attributes affect the alterability of the model. Attributes of models created by novice and expert users are studied and the results are compared. Parent model attributes are considered and compared with those of the altered models; this helps examine the effect of incentives on the attributes and those of the attributes on CAD model alteration – these serve as empirical evidence behind the conclusions drawn. Based on the results of the study useful prescriptions for efficient ways to create CAD models that are also easy to alter are suggested.

CHAPTER III

METHODS

To understand the effect of incentives CAD model creation and the subsequent impact on alteration of the created models, an exercise was carried out with three sets of participants:

- Set 1: 67 students from a junior level CAD course,
- Set 2: 36 students from a senior level CAD course and
- Set 3: 30 product development engineers from an Indian subsidiary of a renowned product development and services company.

The junior-level design course had a laboratory portion where the students used Pro|Engineer Wildfire 4. The laboratory-based senior level course was aimed at teaching students mechanical design methodologies using Solidworks 2009. In both the junior and the senior level courses extra credit in the course was used to incentivize the students. The portion of extra credit to the overall course grade was similar in both courses. Most students in the junior and senior level courses had no prior experience with the CAD software being taught. In both cases, the exercise was carried out towards the end of the semester when the students had been instructed in basic and intermediate part modeling techniques.

The engineers had over 4.9 years of experience in using Pro|Engineer CAD package for product development activities. The incentives to the practicing engineers were not explicit as in the case of the student exercises. The instructions for the exercise flowed from respective managers/team leads. Thus the incentives inherent to their current projects were the incentives to the exercise too.

Participants from the junior level CAD course (Set 1) were divided into two groups (Group 1A and Group 1B), based on their performance on a pervious exercise to ensure that both groups had similar skill level distribution. The participants in Set 2 (Group 2A and Group 2B) and Set 3 (Group 3A and Group 3B) were randomly divided into two groups; however, the average experience level of participants in Groups 3A and 3B was 4.9 years. The exercise was carried out in two phases. In the first phase, Groups 1A, 2A and 3A were told that their goal was to create a 3D model of the component in Figure 4 as quickly as possible. This part is comparable to the one in Chapter 4 of Toogood [50]. In the senior level course, those finishing in the top third of their group would get 100 points (7 points in the junior level course) of extra credit towards their grade; those finishing in the second third would receive 85 points (4 points in the junior level course); those finishing in the bottom third (while putting in at least a good faith effort) would receive 70 extra credit points (2 points in the junior level course). Participants in Groups 1B, 2B and 3B were asked to model the same part (Figure 4) so that it could easily be altered. Groups 1B and 2B (participants from the junior level and senior level courses) were told that only part of their extra credit would be based on how quickly they modeled the component. Those finishing in the top two-thirds of their group would receive 85 points (4 points in the junior level course); those finishing in bottom third would again receive 70 points (2 points in the junior level course - again assuming a good faith effort). However those finishing in the top third would have a chance to receive an additional 15, 7, or 0 points (3, 1 or 0 points in the junior level course) based on how quickly their design could be altered (again based on which third the average of altered design times fell into).

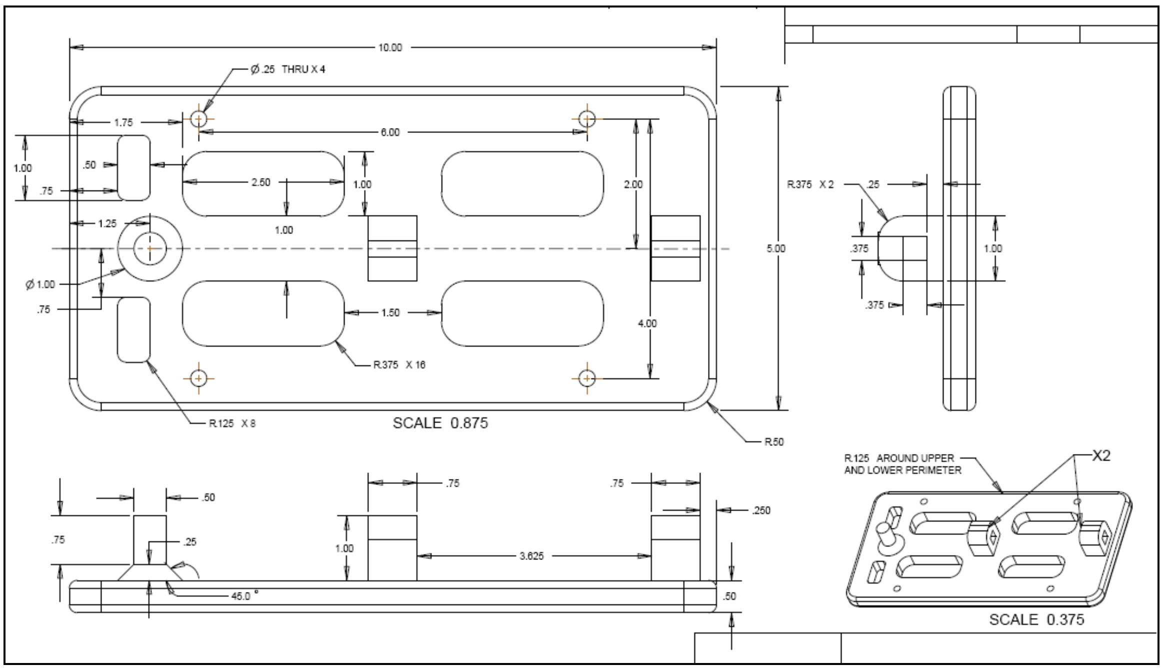

Figure 4 – Drawing of the original design

The participants were unaware of the changes that would be made to the models later on. This emulated the industrial setting where a designer is not aware of the changes the initial design would undergo based on downstream activities, reviews, or product updates. In each phase the participants were given sixty minutes to complete the task. Participants in Groups 1A, 1B, 2A and 2B notified one of the lab instructors when they believed they had completed the exercise and the model was inspected for accuracy. Once the model was deemed accurate, the completion time was noted. The completed models were collected from the participants. Participants in Groups 3A and 3B noted their modeling time themselves and submitted the models with their times to a colleague who collected the models from all the engineers at the end of the exercise.

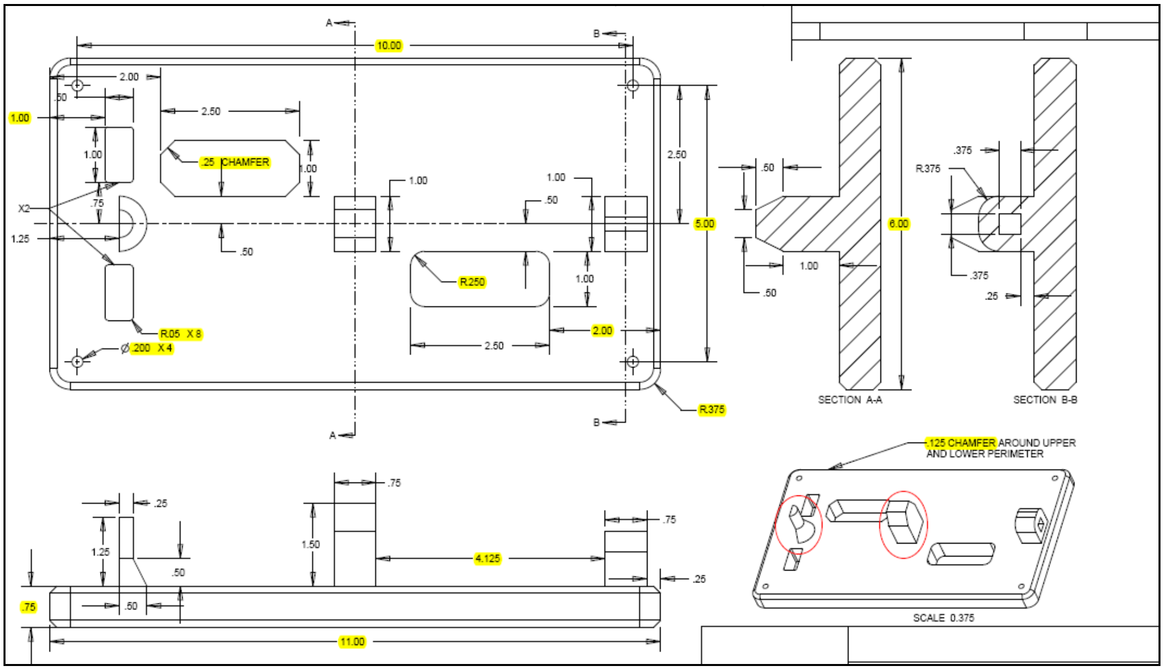

Figure 5 – Drawing of the altered design

The participants were unaware of the changes that would be made to the models later on. This emulated the industrial setting where a designer is not aware of the changes the initial design would undergo based on downstream activities, reviews, or product updates. In each phase the participants were given sixty minutes to complete the task. Participants in Groups 1A, 1B, 2A and 2B notified one of the lab instructors when they believed they had completed the exercise and the model was inspected for accuracy. Once the model was deemed accurate, the completion time was noted. The completed models were collected from the participants. Participants in Groups 3A and 3B noted their modeling time themselves and submitted the models with their times to a colleague who collected the models from all the engineers at the end of the exercise.

In the second phase, the engineers remained divided into the same two groups as in the first phase. The models of those who finished in the top third of each incentive group, based on model quickness, of each group were selected to be used in this alteration phase. Each of the models selected from Groups 1A, 2A and 3A (henceforth referred to as parent models) was assigned to three participants in Groups 1B, 2B and 3B respectively. Similarly, each of the models selected from Groups 1B, 2B and 3B was assigned to three participants in Groups 1A, 2A and 3A respectively. The participants were not aware of which incentive group provided the model they were altering. The assigned models and the drawing shown in Figure 5 were distributed to the participants. They were given sixty minutes to complete alteration of the given model to that shown in Figure 5. Upon completion, the alteration time was noted down and the models (henceforth referred to as altered models) were collected.

Upon completion of the exercise, the participants were asked to assess the model given to them for alteration using three metrics. Specifically, they were asked to rate the intuitiveness of organization and the feature order of the model. This was done using a seven point scale (1 –defined as not at all intuitive; 7 – defined as very intuitive). They were also asked to give an overall rating to the model. This was again done using a seven point scale (1 – signifying the student would dread working with a model like this; 7 – signifying the student would be pleased to work with a model like this). These three metrics quantified aspects of model quality and its ability to be altered; they were considered as proxy ratings for how well design intent was captured in the model. It is assumed that a model that properly conveys design intent would be well structured and easy to understand, even if it is “foreign” to the person altering it. As reported by Salehi and McMahon, poorly structured models are difficult to alter [45]. These ratings attempt to connect model structure and the conveyance of design intent. The participants also rated how the inclusion of a certain type of features to the parent model would have affected the ease of alteration and perception of the model. A copy of the instructions for the first and second phases along with the survey can be found in Appendix A.

To analyze the effects of CAD model attributes on alteration time and procedure, the attributes of both the parent and altered models were tabulated. The attributes were based on those described in Rynne and Gaughran [40] and were slightly modified to reflect aspects unique to the CAD programs used based on the expertise of the author (similar to Johnson and Prasad Diwakaran) [74]. A few derived quantities which were obtained by comparing the attributes of the altered model with its parent model have also been considered. These attributes and quantities are listed and described in Table 2 (some of the key attributes have been **bolded**).

Table 2 – Description of the Model Attributes and Derived Quantities

Attribute	Description	Measure
Correct Initial Sketch Plane	Denotes whether the sketch for main block feature is placed on the top datum in the model	Binary: 1 – yes; 0 – no.
Correct Model Origin	Center of main block feature located at global origin in the model	Binary: 1 – yes; 0 – no.
Correct Base Feature	Main block as first (non-datum) feature in the model	Binary: 1 – yes; 0 – no.
Correct Part Orientation	Orientation of part as shown in drawing in the model	Binary: 1 – yes; 0 – no.
Traditional Feature Sequence	**The model should begin with main block and end with chamfers and rounds**	**Binary: 1 – yes; 0 – no.**
Number of Features	**The total number of features in the model. Sketches are not counted as additional features; pattern features include the pattern, the original feature, any additional required geometry; mirrors are counted as a single feature; all datum features (outside default planes and coordinate system) are included**	**Whole number**
Use of Reference Geometry Features	All datum features (outside default planes and coordinate system) in the model	Whole number
Simple sketch and feature geometry	Average number of sketch segments per extrusion or revolve; rounds and chamfers per feature in the model	Real Number
Average number of segments	The number of sketch segments per feature in the model	Real Number
Number of weak dimensions	**Number of weak sketch dimensions in extrusion or revolve feature in the model. Weak dimensions are created/deleted without notice by the CAD program and hence the name "weak" dimension. When the user defined dimensions and constraints – using the "constructive approach" [75] – were less than the required dimensions to completely constrain the sketch, the number of dimensions required to make the sketch fully defined was counted as the number of weak dimensions.**	**Whole number**
Number of Pattern Features	All pattern features in the model	Whole number

Table 2 continued

Attribute	Description	Measure
Correct Feature Terminations	**Number of features that do not have correct feature terminations (e.g., through holes not defined as such) in the model**	**Whole number**
Number of Mirror Features	Includes both solid and sketched mirror features in the model	Whole number
Relations	Whether or not mathematical relations were used in the model	Binary: 1 – yes; 0 – no.
Number of New Features	The number of new features added to the parent model to get the altered model	Whole Number
Number of Features Deleted	The number of features in the parent model that were deleted during alteration	Whole Number
Percentage of Features Retained	**The percentage of features from the parent model that are retained with or without changes made to them in the altered model**	**Real Number**
Number of Features Unchanged	The number of features that have been carried over to the altered model as is from the parent model	Whole Number
Number of Features Changed	**The number of features in the parent model that have been modified in the altered model**	**Whole Number**
Number of Features Inserted	The number of features that have been inserted between existing features in the model tree in the altered model	Whole Number
Number of New Mirrors	Includes both solid and sketched mirror features newly added to the parent model during alteration	Whole Number
Number of New Patterns	Only the new pattern features added to the parent model during alteration	Whole Number
Number of Mirrors Deleted	Includes both solid and sketched mirror features that have been deleted from the parent model during alteration	Whole Number
Number of Patterns Deleted	The pattern features that have been deleted from the parent model during alteration	Whole Number

Once the exercise (both the first and the second phases) was completed each of the completed models collected from the groups was studied. The model attributes like correct initial sketch plane, correct origin, base feature, number of features and traditional feature sequence were obtained directly from the model tree. Other attributes like the number of weak dimensions, number of sketch segments, incorrect feature termination and number of mirrors were obtained by analyzing every feature in the model tree. For the altered models, a few derived parameters like the number of new features, percentage of features retained and the number of features changed were also calculated. These attributes were calculated by comparing the attributes of each altered model with those of its parent model.

The modeling time, the model attributes, and the derived parameters of both the original and the altered models were compared for any statistically significant differences. The correlations between the above listed variables were also considered to identify the relations between the variables. One tailed probability is used in the analyses due to the unidirectional relevance of the quantities in relation to the expected results. The results obtained from models from the different sets of data are also compared. This comparison between the sets, especially between the Pro|Engineer and the Solidworks sets, is valid given the similarities between the CAD packages. Feature creation in both 3D modeling CAD packages is highly sketch driven; most of the features are created by sketching the geometry of the feature and manipulating the same for alteration. Basic features including extrude, revolve, round, chamfer, mirror, pattern, datum plane and datum axis are common to both the packages. Sketch entities like line, rectangle, circle, arc and fillet and sketch manipulation options like constraints, trim and offset options are also common; there are options available in both packages to manipulate the orientation, display style, color and background of the part. The fundamental difference between the two packages is the user interface – where the options for the above mentioned features and sketch entities are located in the software and how to feed the necessary information for the creation/manipulation of a sketch or a feature. A flowchart of the data collection methodology is presented in Figure 6.

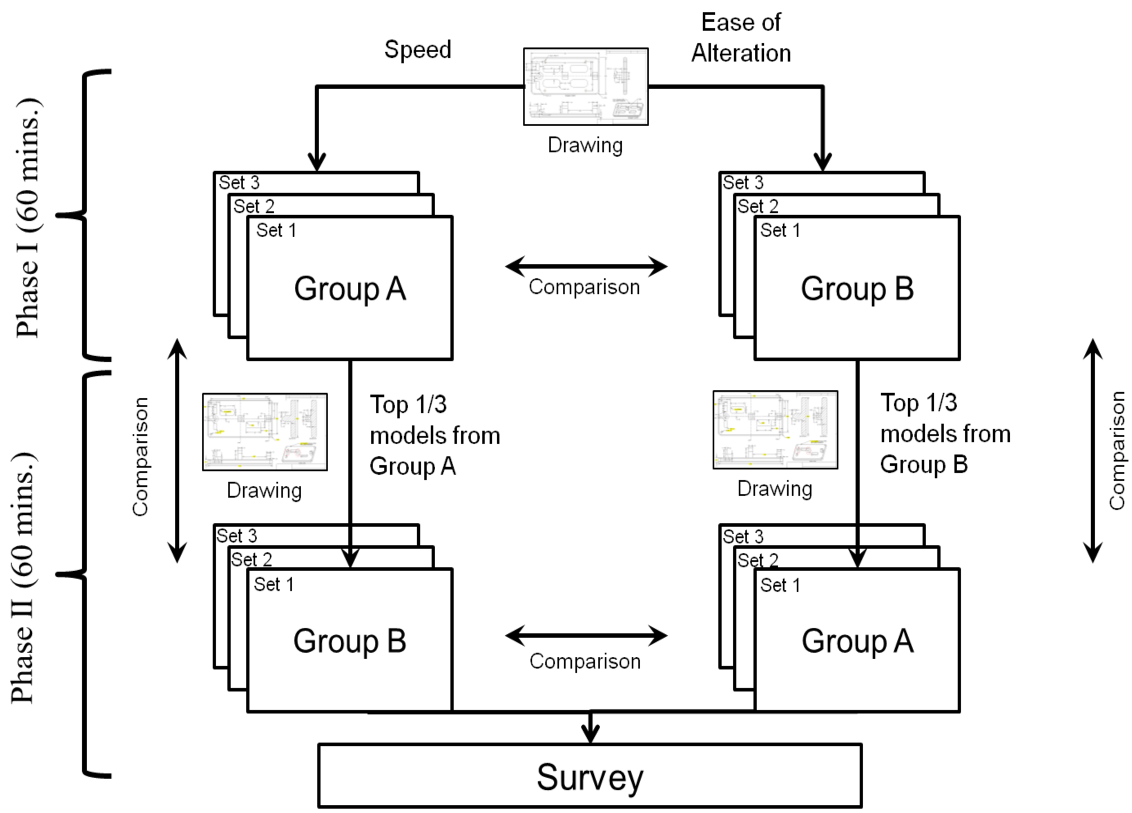

Figure 6 – Flowchart of the methodology employed in this work

The results of the analyses detailing the relationship between model attributes, derived quantities, and assessment metrics are presented in the following chapters.

CHAPTER IV

RESULTS FROM JUNIOR LEVEL CAD COURSE (PRO|ENGINEER)

In this chapter the results of the exercise with the junior level course students are presented. The students used Pro|Engineer Wildfire 4 to create the models in the exercise. The modeling time, the model attributes and the derived parameters of both the original and the altered models were compared for any statistically significant differences. The correlations between the above listed variables were also considered to identify the relations between the variables.

4.1. Original Design

The results of the first phase of the exercise are summarized in Table 3. Of the thirty-three students who were incentivized to create the model as quickly as possible (Group 1A), twenty-three (69.7%) students completed the exercise. The average time required by this group was 35.3 minutes (the standard deviation being 10.3 minutes). Twenty-three of thirty-four (67.6%) students who were incentivized to create the models for ease of alteration (Group 1B) were successful. The average time required by those students was 39 minutes (standard deviation was 8.9). Group 1B students took over 10% more time to complete the exercise. This was expected as Group 1B students would spend additional time adding details to the model so that it would be easy to alter. Four of the thirty-four participants in Group 1B renamed the default features to give them meaningful names so that they are easier to identify during alteration. All the students chose the correct origin and the base feature. Over 90% of Group 1A students chose the correct sketching plane – about 13% more than that of Group 1B. Group 1B students used more features and reference geometry features. Group 1A models had more weak dimensions; this could be attributed to the time saved by not completely constraining the sketched geometry. The differences between these attributes were not statistically significant. Group 1A models had a significantly more segments compared to Group 1B models. No student used relations to relate different features together. The average number of segments was significantly greater in Group 1A models. Group 1B used more mirror features while Group 1A used more pattern features. These differences were statistically significant. One would expect mirrors consume less time than patterns considering the time invested in providing additional information to define patterns.

Table 3 - Statistical t-Tests between Group 1A and Group 1B Model Attributes

	Goal Averages		**t**	**Sig. (1-tailed)***
	Speed (Group 1A)	**Alteration (Group 1B)**		
No. of Students Participating	33	34	-	-
Students Completing the Exercise	23	23	-	-
Time (minutes)	35.3	39.0	1.28	0.103
Standard Deviation	10.3	8.9	-	-
Sketch Plane	0.91	0.78	-1.22	0.114
Orientation	0.74	0.61	-0.93	0.178
No. of Features	16.39	17.61	1.06	0.147
Reference Geometry Features	0.87	1.26	1.17	0.125
Avg. no. of Segments	3.70	3.02	-1.67	**0.053**
Total weak Dimensions	4.78	3.91	-0.48	0.318
Incorrect Feature Terminations	0.91	1.17	0.69	0.248
No. of Mirror Features	2.35	3.35	1.43	**0.079**
No. of Patterns Features	2.17	1.65	-1.07	0.145

α=0.100

Table 4 lists the correlations between the various model attributes and modeling time. The upper number in each cell is the Pearson's correlation coefficient and the lower number is the p-value. Modeling time was significantly positively correlated with the number of weak dimensions and incorrect feature terminations. This was not expected; additional time has to be invested to convert Pro|Engineer generated weak dimensions to strong ones and to ensure that features are correctly terminated. The result could be attributed to the skill level of the junior level students. Modeling time was also significantly positively correlated with the number of mirror features used. Modeling time and the average number of segments were negatively correlated indicating that models with complex features could be modeled quickly. This was in agreement with the claim of Hamade, et al. [41]; however the correlation was not statistically significant. The number of pattern features was significantly negatively correlated with modeling time. Though the modeling time increased with the number of features used the correlation was not statistically significant as one might expect. The orientation and the initial sketch plane used were significantly positively correlated. The number of features and the average number of segments were strongly negatively correlated; this was an expected result. The average number of segments was significantly negatively correlated with incorrect feature terminations, the number of mirrors and the number of patterns. The negative correlation between the number of mirrors and the average number of segments was indicative of the fact that there were significantly more mirror features compared to sketched mirrors. Correct feature terminations were associated with complex sketches; most features were part of a single sketch and did not have to be terminated individually. Mirror and pattern features add to the feature count without increasing the number of segments and would reduce the average number of segments in the model. The number of mirrors and patterns were negatively correlated; students had a strong inclination towards the use of either the mirror or the pattern feature.

Table 4 - Correlations between Attributes of the Original Models from Set 1 participants

	Sketch Plane	Orient-ation	No. of Features	Ref. Geo.	Avg. No. of Sgmts.	Total Weak Dims.	Incorr. Feat. Term.	No. of Mirrors	No. of Patterns
Time	-0.057 0.354	-0.054 0.360	0.131 0.192	0.020 0.448	-0.111 0.232	**0.288 0.026**	**0.446 0.001**	**0.245 0.050**	**-0.301 0.021**
Sketch Plane		**0.609 0.000**	-0.079 0.302	-0.136 0.183	0.080 0.299	-0.036 0.407	0.015 0.462	-0.155 0.152	0.162 0.141
Orientation			0.133 0.190	**-0.206 0.085**	-0.083 0.291	-0.143 0.171	0.024 0.437	0.034 0.412	0.076 0.307
No. of Features				0.145 0.168	**-0.710 0.000**	-0.153 0.156	**0.335 0.012**	**0.506 0.000**	0.072 0.316
Ref. Geo.					**-0.203 0.088**	**0.212 0.079**	-0.002 0.495	-0.021 0.446	0.109 0.236
Avg. No. of Sgmts.						-0.081 0.297	**-0.303 0.020**	**-0.451 0.001**	**-0.251 0.046**
Total Weak Dims.							**0.275 0.032**	0.048 0.377	-0.078 0.304
Incorr. Feat. Term.								**0.357 0.007**	-0.166 0.136
No. of Mirrors									**-0.569 0.000**

4.2. Altered Design

The alteration time, model attributes and derived parameters of the models altered by Group 1A and Group 1B were compared and the results are summarized in Table 5. Fifteen of the thirty-three students (45.45%) who attempted to alter the models created by students incentivized for speed (Group 1B). Twenty-two of thirty two students (68.75%) were successful in implementing the changes to models created for ease of alteration (Group 1A). This was an expected result as the models altered by Group 1A students were created for the ease of alteration. The time required to alter the model by Group 1B was significantly greater than the time required by Group 1A students. The models that were created for ease of alteration were indeed easier to alter.

Table 5 – Statistical t-Tests between Group 1B and Group 1A Model Attributes

	Goal Averages		t	Sig. (1-tailed)*
	Speed (Group 1B)	Alteration (Group 1A)		
Number of Students Participating	33	32	-	-
Number of Students Completing	15	22	-	-
Alteration Time (minutes)	43.03	35.42	-2.30	**0.014**
Sketch Plane	1.00	0.67	-3.16	**0.002**
Orientation	0.87	0.57	-2.06	**0.023**
Number of Features	17.73	18.90	1.29	**0.103**
Reference Geometry Features	1.27	2.14	2.11	**0.021**
Avg. No. of Segments	3.53	3.44	-0.45	0.326
Total Weak Dimensions	4.07	3.67	-0.35	0.366
Incorrect Feature Terminations	0.53	0.48	-0.33	0.372
No. of Mirror Features	1.73	1.38	-0.75	0.230
No. of Pattern Features	0.53	1.00	1.59	**0.061**
No. of New Features	9.87	9.14	-0.55	0.292
No. of Features Deleted	7.47	9.10	1.29	**0.103**
Percentage Retention	48.51	53.93	0.85	0.201
No. Retained Without Change	2.20	3.29	1.56	**0.064**
No. of Original Features Changed	5.60	6.43	0.96	**0.171**
No. of Mirrors Deleted	0.87	1.43	1.09	**0.143**
No. of Patterns Deleted	0.93	1.81	1.88	**0.034**
Intuitive Organization	3.80	4.69	2.96	**0.004**
Intuitive Order	3.91	4.52	2.29	**0.014**
Overall	4.03	4.63	2.09	**0.022**

$\alpha=0.100$

Group 1B models had the correct sketch plane chosen and the orientation maintained. The parent models had these differences built into them which were propagated to the altered models. As an example, all parent models given to Group 1B had the correct sketch plane chosen and hence all the altered models also had the correct sketching plane. Parent models created for ease of alteration required more features overall to be altered. This could be attributed to the few, complex features used in Group 1B parent models. Group 1A models also had a significantly higher number of reference geometry features. Though not statistically significant, the percentage of features retained was greater for Group 1A. The number of features retained without change and those altered by Group 1A were significantly greater than that for Group 1B. More mirrors and patterns were deleted by Group 1A students. This could be linked to the kind of changes that were required to alter the parent model. The models created for the ease of alteration were perceived better than those created quickly. This could be validated by the intuitive order, intuitive organization and overall ratings these models received which were all significantly higher for models altered by Group 1A (which were created for the ease of alteration). It should be noted that there were very few new mirror and pattern features created during alteration and hence these derived parameters were not included in the analysis.

Table 6 lists the correlations between various model attributes, derived attributes, alteration time and the design intent proxy ratings. Some of the important results are discussed below. Models with more features, more mirrors and more patterns took longer to be altered. The average number of segments was negatively correlated with

Table 6 – Correlations between Attributes of the Altered Models from Set 1 Participants

	Sketch Plane	Orient-ation	No. of Feat.	Ref. Geo.	Avg. no. of Sgmts.	Tot. Weak Dims	Incorr. Feat. Term.	No. of Mirrors	No. of Patt.	No. of New Feat.	No. of Feat. Del.	% Retent-ion	No. Retnd. w/o Chg.	No. of Feat. Chg.	Int. Org.	Int. Order	Over-all
Alt. Time	0.017	-0.198	**0.237**	0.127	**-0.339**	0.145	0.020	**0.276**	0.175	**0.250**	0.185	**-0.232**	0.070	-0.152	**-0.357**	**-0.273**	-0.137
	0.462	0.124	**0.082**	0.231	**0.022**	0.199	0.455	**0.052**	0.153	**0.071**	0.140	**0.086**	0.342	0.188	**0.016**	**0.054**	0.214
Sketch Plane		**0.741**	**-0.265**	0.080	0.195	0.081	0.070	-0.170	-0.189	-0.128	**-0.238**	0.102	-0.039	0.016	**0.221**	-0.095	-0.051
		0.000	**0.059**	0.322	0.127	0.320	0.342	0.161	0.135	0.229	**0.081**	0.277	0.410	0.462	**0.097**	0.291	0.384
Orientation			-0.145	-0.021	0.162	0.166	0.181	0.036	**-0.354**	-0.081	**-0.253**	0.147	-0.111	0.094	**0.274**	-0.052	0.015
			0.200	0.451	0.172	0.167	0.146	0.418	**0.017**	0.319	**0.068**	0.195	0.259	0.293	**0.053**	0.381	0.464
No. of Feat.				0.093	**-0.773**	0.061	0.094	**0.420**	**0.236**	**0.339**	**0.373**	-0.063	**0.258**	**0.335**	-0.098	-0.051	0.036
				0.295	**0.000**	0.362	0.294	**0.005**	**0.083**	**0.022**	**0.013**	0.357	**0.064**	**0.023**	0.284	0.383	0.417
Ref. Geom.					-0.153	0.057	**-0.262**	**-0.349**	**0.460**	-0.129	0.081	0.139	0.175	0.162	**0.250**	0.136	**0.367**
					0.187	0.371	**0.061**	**0.019**	**0.002**	0.226	0.320	0.209	0.153	0.172	**0.071**	0.214	**0.014**
Avg. No. of Sgmts.						**0.235**	**-0.295**	**-0.489**	**-0.383**	**-0.252**	**-0.391**	0.140	-0.195	**-0.290**	0.132	**0.256**	-0.148
						0.084	**0.040**	**0.001**	**0.011**	**0.069**	**0.009**	0.207	0.128	**0.043**	0.222	**0.066**	0.195
Tot. Weak Dims							-0.083	0.068	-0.211	**-0.232**	-0.130	**0.277**	**0.358**	0.065	**0.296**	**0.407**	0.063
							0.314	0.346	0.108	**0.087**	0.226	**0.051**	**0.016**	0.354	**0.040**	**0.007**	0.358
Incorr. Feat. Term.								**0.346**	-0.095	-0.029	0.007	0.001	**0.241**	-0.055	0.005	**-0.381**	-0.090
								0.019	0.291	0.433	0.485	0.497	**0.078**	0.374	0.488	**0.011**	0.301
No. of Mirrors									**-0.356**	0.218	**0.241**	-0.161	**0.267**	-0.126	-0.071	-0.118	0.035
									0.017	0.101	**0.079**	0.174	**0.058**	0.231	0.341	0.247	0.419
No. of Patterns										-0.200	-0.092	0.234	0.135	**0.462**	-0.084	-0.075	0.079
										0.121	0.296	0.084	0.216	**0.002**	0.314	0.332	0.323
No. of New Feat.											**0.610**	**-0.854**	**-0.574**	**-0.585**	**-0.258**	**-0.417**	-0.069
											0.000	**0.000**	**0.000**	**0.000**	**0.065**	**0.006**	0.344
No. of Feat. Deleted												**-0.764**	-0.140	**-0.403**	-0.040	-0.149	-0.034
												0.000	0.207	**0.007**	0.408	0.193	0.423
% Retention													**0.569**	**0.719**	**0.291**	**0.428**	0.137
													0.000	**0.000**	**0.042**	**0.005**	0.212
Retained w/o Chng.														**0.248**	**0.246**	**0.275**	0.109
														0.072	**0.074**	**0.052**	0.264
No. of Feat. Changed															0.145	**0.310**	0.092
															0.199	**0.033**	0.296
Int. Org.																**0.605**	**0.651**
																0.000	**0.000**
Int. Order																	**0.474**
																	0.002

α=0.100

alteration time – models with a few complex sketched features were altered quicker than ones with several simpler features. The design intent proxy ratings were all negatively correlated with the alteration time. This implied that models which were well organized and had intuitively ordered features were easy to alter. The overall rating was not statistically significantly correlated. The number of mirrors, patterns and new features contributed positively to the overall number of features as one would expect. The number of features was positively correlated with the number of features deleted. This could be the result of deleted features being replaced with more new features. The above results were statistically significant. Though the number of features was negatively correlated with intuitive order and organization ratings, the correlation was not statistically significant. Reference geometry features were retained even if they were not being used during the alteration procedure. They added to the number of features retained without change though the correlation was not statistically significant. The number of reference geometry features used was significantly positively correlated with the design intent proxy ratings with only the intuitive order rating not being statistically significant. Reference geometry features were used with appropriate features and hence the parts were rated high on design intent conveyance. The total number of weak dimensions increased with the average number of sketch segments. In most instances deleting unwanted sketch segments during alteration resulted in weak dimensions which were not converted to strong ones. With the increase of mirrors and patterns, the average number of segments decreased. This was because mirrors and patterns contributed to the feature count without adding to the number of segments. The number of new features added also reduced the average number of segments.

Intuitive organization and order ratings were positively correlated with the average number of segments while the latter was statistically significant. Models with fewer, more complex features were easily ordered and organized. The number of weak dimensions was negatively correlated with the number of new features. This result strengthens our claim that a majority of the weak dimensions originated while sketches were modified by deleting existing sketch segments.

There was a strong positive correlation between the incorrect feature terminations and percentage of features retained indicating that errors in feature terminations were carried over during alteration. Even in the altered models, the number of mirrors and patterns were negatively correlated indicating that students either preferred mirrors or patterns. The number of mirrors and patterns did not seem to affect the design intent proxy ratings. As one would expect, the number of new features was negatively correlated with the percentage of features deleted. New features were required to replace deleted features and to incorporate certain modifications. All altered models had features deleted from the parent model and new features added; this was in part imposed by the altered design. However, the number of new features added was negatively correlated with the intuitive order, organization and overall ratings for the model. This was justified because several of the changes could be made through modification of existing features. The need for new features suggested that some of the features were perceived not suitable for modification and hence received the poor ratings. However, the overall rating was not significantly negatively correlated. The design intent proxy ratings were all positively correlated with the percentage of features retained with only the overall rating not statistically significantly correlated. Models which had several features that could easily be altered or retained, received high ratings. The design intent proxy ratings were all significantly positively correlated with one another. This was obvious as models that were had well-ordered and organized features received high overall ratings.

4.3. Comparison with Parent Models

Since each parent model was altered by three different students, the attributes of the altered models were dependent on those of their parent models. Each of the attributes of the parent model was compared with the average of the attributes of the three (or less depending upon how many students completed the alteration exercise) corresponding altered models. The paired t-test was used for this comparison. It should be noted that there are small differences in numbers for the same attributes in Table 3, Table 5, Table 7 and Table 8; this because Table 3 and Table 5 list the average for the attributes whereas Table 7 and Table 8 list the average of averages of the attributes of the altered models corresponding to each parent model. In all altered models, the base feature, the initial sketch plane, and the orientation remained unaltered – these were not changed even if model was incorrectly oriented.

4.3.1. Parent Models Designed for Speed

There were significantly more features and reference geometry features in the altered models and the differences were statistically significant. The students added simple features and geometry that were needed to incorporate the alterations in the parent model. The altered models had fewer segments on an average; however the difference was not statistically significant. The simple features and the reference geometry features added during alteration contributed to this reduction. There were about 56% more weak dimensions in the altered models. There were over 28% more features incorrectly terminated; these differences were not statistically significant. The number of mirrors was reduced by 19.4% and the number of patterns was reduced by 69.1%. These could be strongly related to the altered design.

Table 7 - Comparison of Model Attributes between Altered Models and Parent Models (Incentivized for Speed in Set 1)

Model Attribute	Parent	Altered	t	Sig. (1-tailed)*
Number of Features	15.75	17.96	-1.91	**0.041**
Reference Geometry Features	0.58	1.25	-2.86	**0.008**
Average No. of Segments	4.11	3.50	1.04	0.161
Total Weak Dimensions	2.75	4.29	-0.83	0.212
Incorrect Feature Term.	0.42	0.54	-0.61	0.277
No of Mirrors	2.17	1.75	1.10	0.147
No of Patterns	1.75	0.54	3.89	**0.001**

**α=0.100*

4.3.2. Parent Models Designed for Ease of Alteration

Table 8 – Comparison of Model Attributes between Altered Models and Parent Models (Incentivized for Ease of Alteration in Set 1)

Parent Model	Parent	Altered	t	Sig. (1-tailed)*
Number of Features	18.60	18.85	-0.32	0.379
Reference Geometry Features	1.80	2.32	-1.63	**0.069**
Average No. of Segments	3.10	3.39	-1.42	**0.094**
Total Weak Dimensions	0.20	3.42	-4.29	**0.001**
Incorrect Feature Term.	0.40	0.57	-1.17	0.136
No of Mirrors	2.70	1.32	1.92	**0.043**
No of Patterns	2.20	1.10	1.85	**0.049**

**α=0.100*

Interestingly, in the models incentivized for the ease of alteration, the number of features in both the parent and altered models were within 1.3%. This could be attributed to the high number of features of the parent models. Since the parent models were created using simple features, features could easily be altered or had to be replaced. Complex features would have needed modification of the sketches and addition of new features thereby increasing the feature count of the altered models. There were significantly more reference geometry features and a higher average number of segments in the altered models. There were over seventeen times more weak dimensions in the altered models. This could be indicative of the effect of the lack of incentives. The mirrors and patterns in the altered models reduced by about 50% and the differences were statistically significant. Of the seven models that were chosen as parent models for alteration, five had meaningfully named features. During alteration, there was not a single instance where the newly added features were renamed. The removal of incentives to ensure the ease of alteration of models could be attributed as the reason for this.

CHAPTER V

RESULTS FROM SENIOR LEVEL CAD COURSE (SOLIDWORKS)

In this chapter the results of the exercise with student from the senior level CAD course as participants are presented. The students used Solidworks 2009 for creating the models in the exercise. The modeling time, the model attributes and the derived parameters of both the original and the altered models were compared for any statistically significant differences. The correlations between the above listed variables were also considered to identify the relations between the variables. The students were randomly divided into groups unlike in the case of the junior level students who were divided based on their performance on a previous exercise. It must be noted that this could have resulted in a skill level differential between the groups.

5.1. Original Design

The results of the first phase of the exercise are summarized in Table 9. Twenty of twenty-one (95.2%) students who were incentivized to create the model as quickly as possible (Group 2A) completed the exercise. The average time required by this group was 29.6 minutes (standard deviation was 10.7). All of the fifteen students who were incentivized to create the models for the ease of alteration (Group 2B) were able to complete the exercise. They required 33.1 minutes on an average to complete the task (standard deviation was 8.2). The difference in modeling time between the two groups was not statistically significant. Only about 85% of the students in Group 2A chose the correct sketching plane while there were only 67% of Group 2B students who did so. Eight of the fifteen students in Group 2B renamed the default feature names to assign meaningful names to the features. All students chose the correct base feature. Surprisingly, more than half the students in both groups chose the incorrect origin for the base feature. These differences however, were not statistically significant.

Table 9 – Statistical t-Tests between Group 2A and Group 2B Model Attributes

	Goal Averages		t	Sig (1-tailed)*
	Speed (Group 2A)	Alteration (Group 2B)		
No. of Students Participating	21	15	-	-
Students Completing the Exercise	20	15	-	-
Time (minutes)	29.6	33.1	-1.054	0.150
Standard Deviation	10.70	8.20	-	-
Sketch Plane	0.85	0.67	1.220	0.117
Origin	0.45	0.33	0.682	0.250
Orientation	0.85	0.60	1.619	**0.059**
No. of Features	12.15	12.27	-0.099	0.461
Reference Geometry Features	1.40	1.53	-0.228	0.410
Avg. no. of Segments	5.59	6.04	-0.594	0.278
Total weak Dimensions	5.35	11.07	-1.495	**0.076**
Incorrect Feature Terminations	0.85	0.73	0.838	0.204
No. of Mirror Features	0.35	0.67	-0.977	0.170
No. of Pattern Features	0.20	0.27	-0.298	0.384

$\alpha=0.100$

About 18% more students from Group 2A oriented their models correctly and the difference was statistically significant. Both groups used approximately the same number of features (just over twelve) and reference geometry features. Group 2B models had features with slightly greater number of segments per feature. These differences were not statistically significant. Interestingly, there were significantly more weak dimensions in Group 2B models. This was not expected since Group 2B participants were incentivized to create the models so that they would be easy to alter. Sketches not completely constrained, are perceived as difficult to alter. Weak dimensions were in part due to filleting rectangles in the sketch mode to create rounds in the horizontal and vertical slots and in part due to the way sketch geometry are handled in Solidworks. Unlike Pro|Engineer, in Solidworks there are no explicit weak dimensions displayed if the sketch is not completely constrained. Students who were not aware of how to completely constrain their sketches left them unconstrained. There was no statistically significant difference between the number of incorrectly terminated features, the number of mirror features and the number of pattern features used by the groups. It should be noted that there were no relations used by the students to relate different features together.

The correlations between the various model attributes and the modeling time are listed in Table 10. The upper number in each cell is the Pearson's correlation coefficient and the lower number is the p-value. The total weak dimensions were significantly positively correlated with modeling time. This was not expected because one would expect that time could be saved by not completely constraining sketches used to build features. As expected, the initial sketch plane was strongly positively correlated with model orientation. The number of features and reference geometry features were significantly positively correlated. The number of features was significantly negatively correlated with average number of segments as one would expect. The number of features was negatively correlated with the number of incorrect feature terminations; the correlation was not statistically significant. The number of mirrors and patterns contributed positively to the total number of features. The latter was not statistically significantly correlated. The average number of segments was significantly positively correlated with the total number of weak dimensions. With the sketch growing in complexity, one would expect more weak dimensions in the sketch. It is worth mentioning that there were eight models with the features meaningfully named by Group 2B participants; Group 2A models had Solidworks default names for the features.

Table 10 – Correlations between the Attributes of the Original Models from Set 2

	Sketch Plane	Origin	Orient -ation	No. of Feat.	Ref. Geo.	Avg. No. of Sgmts.	Tot. Weak Dims.	Incorr. Feat. Term.	No. of Mirr.	No. of Patt.
Time	**-0.230** **0.092**	-0.123 0.241	-0.217 0.105	0.097 0.289	0.134 0.222	-0.174 0.158	**0.495** **0.001**	-0.012 0.473	0.017 0.462	-0.176 0.155
Sketch Plane		-0.111 0.263	**0.925** **0.000**	0.073 0.339	-0.178 0.153	0.065 0.356	-0.157 0.183	**-0.272** **0.057**	-0.009 0.480	0.196 0.130
Origin			-0.187 0.141	**0.229** **0.093**	0.021 0.452	**-0.225** **0.097**	**-0.230** **0.092**	-0.029 0.434	0.147 0.200	0.165 0.172
Orientation				-0.062 0.361	-0.153 0.190	0.126 0.235	-0.108 0.269	-0.131 0.227	-0.197 0.129	0.211 0.111
No. of Feat.					**0.551** **0.000**	**-0.808** **0.000**	-0.184 0.146	-0.204 0.120	**0.599** **0.000**	0.219 0.103
Ref. Geo.						**-0.461** **0.003**	0.068 0.350	-0.206 0.117	0.083 0.317	-0.072 0.341
Avg. No. of Sgmts.							**0.233** **0.089**	0.180 0.150	**-0.537** **0.000**	-0.115 0.255
Tot. Weak Dims.								-0.031 0.430	**-0.287** **0.047**	0.148 0.199
Incorr. Feat. Term.									0.033 0.426	-0.045 0.399
No. of Mirrors										0.211 0.111

α=0.100

5.2. Altered Design

The results of the comparison between the various model attributes and the derived parameters of the altered models are presented in Table 11. It must be noted that the number of students participating in the alteration exercise was not the same as those participating in the first phase due to class absences.

Table 11 - Statistical t-Tests between Group 2B and Group 2A Model Attributes

	Goal Averages		t	Sig. (1-tailed)*
	Speed (Group 2B)	Alteration (Group 2A)		
No. of Students Participating	20	21	-	-
No. of Students Completing	18	16	-	-
Average Alteration Time (in mins.)	35.33	34.39	0.229	0.410
No. of Features	14.17	16.75	-1.696	**0.053**
Reference Geometry Features	1.06	2.44	-2.096	**0.024**
Average Sketch Segments	5.28	4.85	1.077	0.145
No. of Weak Dimensions	8.28	8.44	-.061	0.476
Incorrect Feature Terminations	0.56	0.5	.315	0.377
No. of Mirror Features	0.33	0.63	-.946	0.176
No. of Pattern Features	0.06	0.13	-.697	0.246
Relations	0.22	0.56	-2.087	**0.023**
No. of New Features	7.22	13.44	-1.104	0.143
No. of Features Deleted	4.67	3.31	1.343	**0.094**
Percentage of Features Retained	59.72	68.23	-1.069	0.147
No. of Features Retained w/o Change	1.61	3.56	-1.926	**0.033**
No. of Features Changed	5.11	5.06	.064	0.475
No. of New Patterns	0.06	0.13	-.528	0.301
No. of Mirrors Deleted	0.11	0.06	.369	0.357
No. of Patterns Deleted	0.44	0.13	1.229	0.116
Intuitive Organization	4.41	4.54	-.427	0.336
Intuitive Order	4.59	5.08	-1.749	**0.045**
Overall Rating	4.15	4.94	-2.470	**0.010**

******α=0.100*

Eighteen of the twenty students (90%) that attempted to alter the models created by those incentivized to model quickly completed the alterations in the allotted time. The average time required by these students (Group 2B) to complete the alterations was 35.3 minutes (the standard deviation was 9.7 minutes). Sixteen of the twenty-one students (76%) attempting to alter models originally created by those incentivized for ease of alteration were successful in the allotted time. The average alteration time for this group (Group 2A) was 34.4 minutes (the standard deviation was 13.6 minutes). This was not an expected result, as Group 2A was tasked with altering models that were created with that purpose as the goal. This could be due to the skill differential between the groups (as they were partitioned randomly) or due to the lack of foreknowledge about the type of alteration that would be required. While the average time taken by Group 2A to complete the alteration was less than that of Group 2B, the difference was not statistically significant.

More features were deleted from the parent models of Group 2B; this was an expected and statistically significant result. Those incentivized to model quickly would be more likely to include features that would not be easily altered (and thus would have to be deleted if alteration was required). This is further corroborated by the larger number of features retained without alteration from Group 2A than Group 2B; this result was also statistically significant. Group 2A students tended to use more relations in creating features. The difference between the two groups was statistically significant. This was found to be a common modeling practice in the senior level course (in almost all the cases, the relations were used to make sketched chamfers for the rectangular pockets equal in length). More mirrors and patterns were deleted from the parent model by Group 2B. This result was tied to the parent model design and the altered design that the students were asked to build. From Figure 4 and Figure 5 it could be seen that a few possible mirror and pattern features had been altered. The intuitive order, organization and overall ratings for models altered by Group 2A were higher than those of Group 2B; in the cases of intuitive order and overall rating, this difference was statistically significant.

Table 12 - Correlations between Attributes/Derived Parameters of the Altered Models from Set 2

	Sketch Plane	Orient-ation	No. of Feat.	Ref. Geo.	Avg. No. of Sgmts.	Tot. Weak Dims.	Incorr. Feat. Term.	No. of Mirr.	No. of Patt.	No. of New Feat.	No. of Feat. Del.	% Retenti-on	No. Retained w/o Chg.	No. of Original Feat. Chg.	New Patt.	Int. Org.	Int. Order	Over-all
Alteration Time	-0.119 0.252	-0.038 0.415	**0.485** **0.002**	-0.126 0.239	**-0.536** **0.001**	**0.343** **0.023**	0.114 0.261	**0.386** **0.012**	**0.404** **0.009**	0.095 0.296	-0.009 0.480	-0.052 0.384	0.159 0.185	-0.026 0.442	**0.345** **0.023**	**-0.484** **0.002**	-0.164 0.177	**-0.381** **0.013**
Sketch Plane		**0.909** **0.000**	0.005 0.488	**-0.393** **0.011**	-0.081 0.324	**-0.268** **0.062**	-0.127 0.237	**0.247** **0.080**	0.144 0.208	0.125 0.240	**0.268** **0.062**	**-0.242** **0.084**	**-0.283** **0.053**	0.054 0.382	0.109 0.269	0.070 0.348	**-0.278** **0.055**	**0.237** **0.088**
Orientation			0.011 0.474	**-0.419** **0.007**	-0.038 0.415	-0.171 0.166	-0.189 0.143	**0.272** **0.060**	0.158 0.185	0.105 0.278	0.129 0.233	-0.084 0.319	-0.204 0.123	0.153 0.194	0.120 0.249	-0.003 0.493	-0.163 0.178	**0.285** **0.051**
No. of Features				**0.388** **0.012**	**-0.783** **0.000**	**0.460** **0.003**	0.097 0.292	**0.665** **0.000**	**0.502** **0.001**	0.129 0.234	-0.148 0.202	0.189 0.143	**0.630** **0.000**	0.046 0.398	**0.547** **0.000**	**-0.293** **0.046**	-0.008 0.481	-0.057 0.375
Ref. Geo					**-0.316** **0.035**	**0.300** **0.042**	**0.255** **0.073**	-0.057 0.374	-0.060 0.367	-0.073 0.342	0.007 0.485	-0.025 0.445	**0.433** **0.005**	**-0.356** **0.019**	0.077 0.332	-0.067 0.354	0.155 0.191	0.023 0.448
Avg. No. of Segmts.						-0.202 0.126	**-0.295** **0.045**	**-0.561** **0.000**	**-0.462** **0.003**	**-0.242** **0.084**	-0.011 0.476	-0.006 0.486	**-0.483** **0.002**	0.044 0.402	**-0.293** **0.046**	**0.250** **0.077**	-0.006 0.486	0.054 0.381
Tot. Weak Dims.							-0.058 0.372	0.006 0.486	-0.015 0.467	0.047 0.396	-0.150 0.198	0.015 0.467	0.116 0.257	-0.036 0.420	0.116 0.257	**-0.353** **0.020**	-0.069 0.348	-0.218 0.108
Incorrect Feat. Term.								-0.031 0.430	0.086 0.315	-0.153 0.194	0.009 0.479	-0.075 0.336	0.129 0.233	-0.123 0.244	-0.093 0.301	-0.138 0.218	-0.173 0.164	-0.176 0.160
No. of Mirrors									**0.657** **0.000**	-0.031 0.430	-0.165 0.176	**0.299** **0.043**	**0.582** **0.000**	0.115 0.259	**0.678** **0.000**	-0.141 0.213	0.019 0.457	0.023 0.450
No. of Patterns										-0.010 0.478	-0.039 0.414	0.187 0.145	**0.331** **0.028**	**0.270** **0.061**	**0.482** **0.002**	-0.085 0.317	0.065 0.358	0.011 0.475
No. of New Feat.											0.183 0.150	**-0.239** **0.086**	-0.067 0.354	**-0.237** **0.089**	0.065 0.358	-0.100 0.287	-0.074 0.338	-0.033 0.426
No. of Feat. Deleted												**-0.875** **0.000**	**-0.414** **0.007**	**-0.603** **0.000**	-0.056 0.376	0.046 0.397	-0.099 0.289	-0.083 0.321
% Retention													**0.606** **0.000**	**0.739** **0.000**	0.059 0.370	0.196 0.133	**0.355** **0.020**	**0.315** **0.035**
No. Retained w/o Chg.														0.124 0.242	**0.305** **0.040**	0.122 0.245	**0.421** **0.007**	**0.265** **0.065**
No. of Original Feat. Chg.															-0.117 0.255	**0.253** **0.074**	**0.242** **0.084**	**0.355** **0.020**
New Patterns																**-0.295** **0.045**	-0.199 0.130	-0.173 0.164
Int. Org																	**0.763** **0.000**	**0.811** **0.000**
Int. Order																		**0.775** **0.000**

α=0.100

Table 12 summarizes the correlations among the alteration time, various model attributes, derived quantities, and the ratings for the parent models. Only those models where the alteration was completed were considered for this analysis. Statistically significant correlations of note are detailed below. The average number of segments and alteration time were statistically significantly negatively correlated. With a high number of sketch segments per sketch, deleting unwanted sketch elements and conditioning the sketch to match the altered design was a time intensive task. In addition, this was in agreement with the previous result – more segments will result in lesser features and hence less time. The number of weak dimensions and the alteration time were also positively correlated. Weak dimensions can cause alterations to produce unpredictable results, thus increasing alteration time. The number of mirrors and patterns were positively correlated with the alteration time; the presence of these features required additional alteration time.

The number of features and the intuitive organization rating were negatively correlated. While Rynne and Gaughran promote simple sketches (and thus more features) [40]; it seems that these features have a negative effect on the perception of organization. It is interesting to note that for this data set the number of features does not significantly affect either of the other ratings. In models that received better ratings, it is assumed that the design intent has been conveyed well. Those models had lower alterations times and higher percentages of retained features. Intuitive order, organization and the overall ratings were all negatively correlated with alteration time; with only intuitive order, not being statistically significant.

5.3. Comparison with Parent Models

Since each parent model was altered by three different students, the attributes of the altered models were dependent on those of their parent models. Each of the attributes of the parent model was compared with the average of the attributes of the three (or less depending upon how many students completed the alteration exercise) corresponding altered models. The paired t-test was used for this comparison. It should be noted that the averages for attributes in Table 9 and Table 11 are slightly different from those for the same attributes in Table 13 and Table 14; this because Table 9 and Table 11 list the average for the attributes whereas Table 13 and Table 14 list the average of averages of the attributes of the altered models corresponding to each parent model. In all altered models, the base feature, the initial sketch plane, and the orientation remained unaltered – these were not changed even if model was incorrectly oriented.

5.3.1. Parent Models Designed for Speed

Table 13 – Comparison of Model Attributes between Altered Models and Parent Models (Incentivized for Speed in Set 2)

Model Attribute	Parent	Altered	Mean Difference	t	Sig. (1-tailed)*
Number of Features	11.30	14.14	-2.84	-3.198	**0.009**
Reference Geometry Features	0.43	1.24	-0.81	-2.072	**0.041**
Average No. of Segments	6.20	5.21	0.99	1.721	**0.068**
Total Weak Dimensions	1.71	7.48	-5.77	-2.967	**0.013**
Incorrect Feature Term.	0.86	0.57	0.29	2.521	**0.023**
Relations	0.00	0.19	-0.19	-1.333	0.115

*$\alpha=0.100$

When Group 2B altered models were compared with parent models, the average number of features and reference geometry features in the altered models were statistically significantly greater than those in the parent models. Both new features and reference geometries were added to the altered model. In most cases the reference geometries used to create the parent model were not deleted and were carried over as unnecessary features which also contributed to the difference. The average number of segments in the altered models was less and was in agreement with the reasoning that more features will mean fewer segments per feature. The total number of weak dimensions was much higher (over four times) in the case of the Group 2B models. This was due to the deletion of numerous sketch segments of the parent model to make changes to a feature without making necessary changes to the remaining segments. Incorrect feature terminations in the parent models were corrected during alteration resulting in fewer incorrect feature terminations. The number of relations increased in the altered models for Group 2B; however, this increase was not statistically significant.

5.3.2. Parent Models Designed for Ease of Alteration

In Group 2A models, the trend in the results was similar. There were more features in the altered models. The increase in the number of features in the altered models for Group 2A was greater than that of Group 2B. The number of reference geometry features was also higher for Group 2A. There was a marked increase in the number of weak dimensions. A significant number of incorrect features terminations were corrected and new relations were introduced. As mentioned earlier, the relations were not relating different features together – they were found to be a result of a general practice of the senior-level class.

Table 14 – Comparison of Model Attributes between Altered Models and Parent Models (Incentivized for Ease of Alteration in Set 2)

Model Attribute	Parent	Altered	Mean Difference	t	Sig. (1-tailed)*
Number of Features	11.43	16.07	-4.64	-3.352	**0.008**
Reference Geometry Features	1.57	2.24	-0.67	-1.653	**0.075**
Average No. of Segments	6.66	4.97	1.69	1.703	**0.070**
Total Weak Dimensions	4.28	8.10	-3.82	-2.257	**0.032**
Incorrect Feature Term.	0.86	0.48	0.38	2.562	**0.021**
Relations	0.14	0.52	-0.38	-2.066	**0.042**

*$\alpha = 0.100$

Overall, the relationships between the altered and the parent models were not significantly different for the two groups. In both cases, features were added (as opposed to altered). These features were more complex than those of the parent model; this is evidenced by the decrease in the number of sketch segments in both cases. The similarity of the alteration procedure points towards an independence of alteration method from model creation procedure. The removal of alternative incentives could be responsible for this similarity in alteration procedure.

CHAPTER VI

RESULTS FROM PRACTICING PROFESSIONALS (PRO|ENGINEER)

In this chapter the results of the exercise with practicing engineers as participants are presented. The engineers used Pro|Engineer Wildfire 2 and Wildfire 4 for creating the models in the exercise. The modeling time, the model attributes and the derived parameters of both the original and the altered models were compared for any statistically significant differences. The correlations between the above listed variables were also considered to identify the relations between the variables. Like in the senior level exercise, the experienced engineers were also randomly divided into groups which could have resulted in a skill level differential between the groups.

6.1. Original Design

All 15 engineers in Group 3A (incentivized for speed) completed the exercise. The average completion time was 16.64 minutes with a standard deviation of 5.42. In Group 3B (incentivized for ease of alteration) again, all 15 engineers completed the task with an average time of 20.85 mins and a standard deviation of 6.49. A list of the various model attributes collected from Group 3A and Group 3B models is provided in Table 15. Group 3B engineers on average required 25% more time to complete the exercise than Group 3A engineers. This was an expected result. All engineers retained the default names for the features. Only about 47% of the engineers in Group 3A chose the correct initial sketch plane and this affected the orientation of their model. About 60% of the participants in Group 3B chose the correct sketch plane. Choosing the initial sketching plane could be based on each engineer’s experience with reading drawings. The author, who has extensive experience with Pro|Engineer, determined that the part shown in Figure 1 could be modeled with just five features. On an average Group 3A and Group 3B models had 12.33 and 12.73 features, respectively. Models from both groups had approximately the same number of features. Overall, there was less than one reference geometry features (datum planes, datum axes, datum points) per model used by either group.

Table 15 - Statistical t-Tests between Group 3A and Group 3B Model Attributes

	Goal Averages		t	Sig. (1-tailed)*
	Speed (Group 3A)	Alteration (Group 3B)		
No. of Engineers Participating	15	15	-	-
No. of Engineers completing	15	15	-	-
Time (minutes)	16.64	20.85	-1.929	**0.032**
Experience (years)	4.89	4.91	-0.022	0.491
Sketch Plane	0.47	0.60	-0.714	0.241
Orientation	0.47	0.60	-0.714	0.241
No. of Features	12.33	12.73	-0.414	0.342
Reference Geometry Features	0.80	0.53	0.704	0.244
Avg. No. of Segments	5.85	5.14	1.110	0.141
Total Weak Dimensions	0.53	0.00	1.000	0.167
Incorrect Feature Term.	0.33	0.20	0.807	0.213
Number of Mirrors	2.47	3.13	-0.843	0.204
Number of Patterns	0.80	0.93	-0.260	0.398
Traditional Feature Sequence	0.53	0.67	-0.727	0.237

* $\alpha = 0.100$

Group 3A engineers created more reference geometry features. However, there were six participants in Group 3A who used reference geometry features while there were five in Group 3B. The average number of segments for Group 3A models was slightly greater than that for Group 3B. There were 0.53 weak dimensions left unmodified by Group 3A engineers; this was due to just one engineer contributing all the weak dimensions (8 weak dimensions) to the group's average. There were no weak dimensions in the models from Group 3B. Overall, it could be claimed that experienced engineers generally take care to avoid weak dimensions knowing their detrimental nature. There were fewer incorrect feature terminations in Group 3B models. It should be noted that there were five engineers in Group 3A, who did not terminate features correctly as opposed to just two from Group 3B. Group 3B engineers took more care not to terminate features incorrectly. Using mathematical equations is a powerful way to relate features together. Once related, any changes made to one feature will automatically be reflected in the other feature(s) related to it; this improves the conveyance of design intent. There were no such mathematical relations used by either of the groups. This could be due to the fact that they were re-creating a design from a drawing and were not designing a part from scratch.

Group 3B engineers used more mirror and pattern features compared to Group 3A engineers. Models created by both groups had several sketched mirror features – the horizontal slots, the vertical slots and the holes were the features that were the commonly created sketched mirror features. Of the 37 mirrors used in Group 3A models, 36 were sketched mirror features. Of the 47 mirrors used in Group 3B models, 43 were sketched. About 67% of the engineers in Group 3B created the features in the right sequence with the rounds and fillets created as the last features while only 53% from

Group 3A did so. Group 3A engineers might have tended to compromise on proper order to complete the model quickly; however, the differences between these attributes were not statistically significant. In other words, both groups have followed comparably the same methodologies on an average in creating the models irrespective of the incentives urging them to achieve different goals.

The correlations between the model attributes are listed in Table 16. The upper number in each cell is the Pearson's correlation coefficient and the lower number is the p-value. As would be expected, the modeling time is negatively correlated with experience; more experienced engineers took less time to complete the task. Including reference geometry features increased the modeling time. The average number of sketch segments is negatively correlated with original modeling time suggesting that more complex features reduce modeling time. This was consistent with the findings of Hamade, et al. [41]. Following traditional feature sequence did not increase the modeling time as one might expect; this could be because features had to be created regardless of the sequence and the sequence was a result of the engineers' thought process. More experienced users tended to use less reference geometry features. The number of features was strongly negatively correlated with the total weak dimensions. Simple features have less or no dimensions (in case of rounds/chamfers) and reduce the occurrence of weak dimensions. The number of mirrors and patterns are negatively correlated – engineers had a preference for either mirrors or patterns. Those who chose to use mirrors did not use patterns and vice versa.

Table 16 – Correlations between Attributes of the Original Models from Set 2

	Exp.	Sketch Plane	Orient -ation	No. of Feat.	Ref. Geom.	Avg. No. of Sgmts.	Tot. Weak Dims.	Incorr. Feat. Term.	No. of Mirr.	No. of Patt.	Corr. Feat. Seq.
Time	**-0.382** **0.019**	**0.334** **0.036**	**0.334** **0.036**	0.226 0.115	**0.449** **0.006**	**-0.314** **0.046**	0.194 0.152	-0.045 0.407	0.198 0.147	-0.055 0.385	0.031 0.436
Experience		0.112 0.278	0.112 0.278	0.096 0.307	**-0.532** **0.001**	0.169 0.186	-0.253 0.089	-0.058 0.379	-0.141 0.228	-0.047 0.403	0.177 0.174
Sketch Plane			**1.000** **0.000**	-0.014 0.471	0.022 0.454	0.028 0.441	0.174 0.179	**-0.342** **0.032**	0.006 0.487	-0.092 0.315	0.191 0.156
Orientation				-0.014 0.471	0.022 0.454	0.028 0.441	0.174 0.179	**-0.342** **0.032**	0.006 0.487	-0.092 0.315	0.191 0.156
No. of Features					0.236 0.105	**-0.831** **0.000**	**-0.400** **0.014**	-0.037 0.423	**-0.434** **0.008**	**0.603** **0.000**	-0.069 0.359
Ref. Geometry						-0.288 0.061	0.061 0.374	**0.348** **0.030**	0.187 0.162	-0.032 0.433	-0.067 0.362
Avg. No. of Segments							0.116 0.270	0.130 0.247	0.182 0.168	**-0.649** **0.000**	**0.262** **0.081**
Tot. Weak Dims.								-0.112 0.278	0.193 0.154	-0.118 0.267	-0.227 0.113
Incorrect Feat. Term.									0.199 0.146	-0.218 0.124	0.185 0.164
No. of Mirrors										**-0.541** **0.001**	0.083 0.331
No. of Patterns											-0.130 0.247

6.2. Altered Design

A summary of the results of the analysis on the attributes and derived parameters of the altered models (obtained after the second phase) is presented in Table 17. As in the first phase, all engineers in both the groups were able to complete the alteration task. Group 3A engineers who worked on parent models (models provided to the engineers for alteration) which were created for ease of alteration took 18.23 minutes on an average (standard deviation 6.12) to complete the alteration. Group 3B engineers, whose parent models were created for speed, took 18.98 minutes (standard deviation 4.16) to complete their task. In no instance was the initial sketch plane or orientation of the parent model altered.

Table 17 – Statistical t-Tests between Group 3B and Group 3A Model Attributes

	Goal Averages		**t**	**Sig. (1-tailed)***
	Speed (Group 3B)	**Alteration (Group 3A)**		
No. of Engineers Participating	15	15	-	**-**
No. of Engineers completing	15	15	-	**-**
Experience (years)	4.91	4.89	-0.022	0.491
Original Time (minutes)	20.85	16.64	-1.929	**0.032**
Alteration Time (minutes)	18.98	18.23	-0.392	0.349
Sketch Plane	0.40	0.60	1.080	0.145
Orientation	0.40	0.60	1.080	0.145
Number of Features	15.07	15.33	0.437	0.333
Reference Geometry Features	0.47	0.60	0.529	0.300
Avg. no. of Segments	4.42	4.21	-0.938	0.178
Total Weak Dimensions	0.47	0.53	0.178	0.430
Traditional Feature Sequence	0.20	0.60	2.366	**0.013**
Incorrect Feature Terminations	0.80	0.13	-2.054	**0.028**
No of Mirrors	1.60	1.67	0.128	0.450
No. of Patterns	0.67	0.53	-0.402	0.345
No. of New Features	7.33	6.60	-0.705	0.243
No. of Features Deleted	3.60	3.20	-0.442	0.332
Percent Retention	68.7	72.7	0.538	0.297
No. Retained w/o Change	0.73	1.27	1.053	0.151
No. of Features Changed	7.07	7.33	0.279	0.392
New Patterns	0.07	0.07	0.000	0.500
New Mirrors	0.40	0.07	-1.364	**0.096**
No. of Features Inserted	1.33	1.67	0.653	0.259
No. of Mirrors Deleted	0.80	1.20	1.120	0.136
No. of Patterns Deleted	0.40	0.73	1.188	0.122
Intuitive Organization	5.07	5.00	-0.130	0.449
Intuitive Order	5.13	5.20	0.142	0.444
Overall	4.87	5.40	1.123	0.135

** $\alpha = 0.100$*

More reference geometry features were added to the parent models during the alteration process by both groups. This could have been due to poor references chosen in the parent models and could have been influenced by the kind of changes imposed on the models. The total number of features per model, the average number of segments, and the total weak dimensions per model were comparable for both groups. There was a significant difference between the groups when it came to maintaining the traditional feature sequence. 60% of those who altered models created for ease of alteration (Group 3A) were able to maintain traditional feature sequence while only 20% from Group 3B did so. There were more incorrect feature terminations in Group 3B models than in Group 3A models.

The percentage of features retained by Group 3A (73%) was greater than that of Group 3B (69%); however, the difference was not statistically significant. The possibility to maintain the traditional feature sequence and higher percentage retention of features indicate that the features in the parent models created for ease of alteration were easier to modify rather than to delete them and introduce new features. Though there is a significant difference in the number of new mirror features, it should be noted that there were only 4 engineers that introduced new mirror features and the result is not indicative of a preference to introduce mirrors during alteration. Engineers often inserted features by moving them up the model tree to maintain traditional feature sequence. The number of such inserted features was slightly greater in Group 3A. More mirrors and patterns were deleted from models created for speed. The mirrors (used predominantly in sketches) and patterns were used to create the horizontal and vertical pockets and the altered configuration could have forced these deletions. The intuitive order and overall ratings for the parent models created for ease of alteration were higher than those created for speed. This was expected; however the difference was not statistically significant.

Table 18 – Correlations between Attributes/Derived Parameters of the Altered Models from Set 2

	Exp.	Sketch Plane	Orient -ation	No. of Feat.	Ref. Geo.	Avg. No. of Sgmts	Weak Dims.	Corr. Feat. Seq.	Incorr . Feat. Term.	No. of Mirror Feat.	No. of Patt. Feat.	No. of New Feat.	No. of Feat. Del.	% Ret.	No. Ret. w/o Chng.	No. of Feat. Chgd.	No. of Feat. Ins.	Int. Org	Int. Ord.	Over-all
Alteration Time	**-0.303** **0.052**	0.147 0.218	0.147 0.218	-0.097 0.305	0.162 0.196	0.194 0.152	**0.304** **0.051**	0.066 0.365	-0.172 0.182	-0.010 0.479	-0.099 0.302	0.170 0.184	-0.023 0.452	-0.067 0.362	-0.179 0.172	-0.164 0.194	0.153 0.210	-0.234 0.107	-0.109 0.282	**-0.366** **0.023**
Experience		**-0.316** **0.045**	**-0.316** **0.045**	-0.125 0.255	**-0.329** **0.038**	0.153 0.209	**-0.326** **0.039**	-0.128 0.250	0.101 0.298	0.067 0.362	-0.036 0.424	-0.021 0.455	-0.026 0.445	-0.046 0.404	-0.002 0.496	-0.103 0.293	**-0.343** **0.032**	-0.180 0.171	-0.026 0.445	-0.145 0.223
Sketch Plane			**1.000** **0.000**	**0.247** **0.094**	**0.597** **0.000**	**-0.283** **0.065**	**0.303** **0.052**	**0.272** **0.073**	**-0.289** **0.060**	-0.218 0.124	-0.076 0.345	**0.324** **0.040**	**0.499** **0.002**	**-0.425** **0.010**	-0.098 0.304	-0.105 0.290	0.172 0.182	-0.074 0.349	0.081 0.336	0.156 0.206
Orientation				**0.247** **0.094**	**0.597** **0.000**	**-0.283** **0.065**	**0.303** **0.052**	**0.272** **0.073**	**-0.289** **0.060**	-0.218 0.124	-0.076 0.345	**0.324** **0.040**	**0.499** **0.002**	**-0.425** **0.010**	-0.098 0.304	-0.105 0.290	0.172 0.182	-0.074 0.349	0.081 0.336	0.156 0.206
No. Feat.					**0.393** **0.016**	**-0.880** **0.000**	0.021 0.457	-0.143 0.226	0.071 0.354	**-0.460** **0.005**	**0.477** **0.004**	0.001 0.497	**0.305** **0.051**	-0.073 0.351	**0.602** **0.000**	**0.290** **0.060**	**0.257** **0.085**	**0.316** **0.044**	0.199 0.146	0.195 0.150
Ref. Geo.						**-0.454** **0.006**	**0.351** **0.029**	**0.264** **0.079**	-0.241 0.100	**-0.294** **0.058**	0.192 0.154	**0.440** **0.007**	**0.675** **0.000**	**-0.593** **0.000**	0.182 0.168	**-0.338** **0.034**	0.110 0.282	0.127 0.251	**0.254** **0.088**	0.111 0.280
Avg. No. of Sgmts.							0.108 0.284	0.045 0.407	0.177 0.175	**0.418** **0.011**	**-0.609** **0.000**	-0.015 0.468	**-0.412** **0.012**	0.180 0.170	**-0.750** **0.000**	-0.119 0.265	-0.221 0.120	**-0.327** **0.039**	-0.174 0.179	-0.201 0.143
Weak Dims.								0.137 0.235	0.000 0.500	0.110 0.282	**-0.306** **0.050**	**0.297** **0.056**	0.182 0.168	-0.211 0.132	-0.221 0.120	-0.172 0.181	0.062 0.373	-0.012 0.474	0.041 0.416	0.026 0.445
Corr. Feat. Seq.									**-0.414** **0.012**	**0.365** **0.024**	**-0.402** **0.014**	0.206 0.137	**0.317** **0.044**	**-0.323** **0.041**	-0.199 0.146	-0.225 0.115	**0.350** **0.029**	0.080 0.336	**0.274** **0.071**	0.233 0.108
Inco. Feat. Term.										**-0.338** **0.034**	0.025 0.448	-0.229 0.112	**-0.265** **0.078**	**0.259** **0.084**	**-0.318** **0.044**	**0.474** **0.004**	-0.133 0.242	**0.308** **0.049**	0.224 0.117	**0.257** **0.085**
No. of Mirrors											**-0.754** **0.000**	**0.250** **0.092**	-0.056 0.384	-0.103 0.294	**-0.372** **0.022**	**-0.380** **0.019**	-0.169 0.186	**-0.333** **0.036**	-0.062 0.373	-0.217 0.124
No. of Patterns												**-0.306** **0.050**	0.060 0.377	0.134 0.241	**0.749** **0.000**	**0.245** **0.096**	0.167 0.189	**0.375** **0.021**	0.000 0.500	0.047 0.402
New. Feat													**0.782** **0.000**	**-0.905** **0.000**	**-0.317** **0.044**	**-0.847** **0.000**	**-0.278** **0.068**	**-0.381** **0.019**	-0.086 0.327	-0.102 0.296
No. of feat. Del.														**-0.946** **0.000**	0.041 0.416	**-0.632** **0.000**	-0.082 0.334	-0.086 0.326	0.089 0.319	0.037 0.424
% Ret.															0.165 0.191	**0.803** **0.000**	0.218 0.124	0.238 0.103	-0.019 0.460	0.046 0.404
No Ret. w/o Chg.																0.144 0.223	0.215 0.127	**0.252** **0.089**	-0.079 0.340	0.000 0.500
# of Feat. Chgd.																	**0.358** **0.026**	**0.455** **0.006**	0.223 0.119	**0.248** **0.093**
Feat. Inserted																		**0.389** **0.017**	0.207 0.136	**0.324** **0.040**
Int. Org.																			**0.711** **0.000**	**0.669** **0.000**
Int. Order																				**0.593** **0.000**

$\alpha = 0.100$

The correlations between altered model attributes and derived parameters are summarized in Table 18. More experienced users were able to alter the CAD models quicker – this was indicated by a significant negative correlation between alteration time and experience. Alteration time increased with the increase in the number of weak dimensions and the number of mirrors deleted; these correlations were statistically significant. The intuitive order, organization and overall ratings were negatively correlated with alteration time – models which required a long time to alter received poor ratings. Only the overall rating was statistically significantly correlated with alteration time. Alteration time was negatively correlated with the number of features retained and modified – by retaining or changing existing features it would be quicker to make changes to a design. However, these were not statistically significant. The number of features was significantly negatively correlated with the number of mirrors since the mirrors were typically sketch based.

The models with more features were rated higher on intuitive order, organization and the overall quality; models with several simple features were perceived as better conveying design intent by those that altered them. But only the correlation with intuitive organization was statistically significant. The number of features deleted was significantly positively correlated with the number of features in the model. The altered design forced some of the features to be deleted from the parent model. In models with complex features, only the sketch of a feature had to be altered while in models with simpler features independent features had to be deleted. The significant positive correlation between the number of features changed and the total number of features indicated that it was easier to make changes to simpler features. The number of weak dimensions increased sharply with the number of mirrors deleted – the deletion of sketched mirrors gave rise to weak dimensions which were not converted to strong ones. Models with the traditional feature sequence were rated high on intuitive order as one would expect. The intuitive organization and overall ratings were also rated high; however these were not statistically significant. As the number of patterns increased, the average number of segments decreased. This was because pattern features do not contribute to the average number of segments.

The models with more patterns and fewer mirrors were perceived as better organized – this was indicated by the significant correlations with the intuitive organization ratings. The average number of segments was negatively correlated with the all the design intent proxy ratings (only the correlation with intuitive order was statistically significant). Again, this supported the notion that more complex features made understanding the model more difficult. Models with more mirrors received lower ratings while those with more patterns received higher ratings. This could be due to the fact that several mirrors created in the sketch mode had to be deleted thus adding to the effort of the altering engineer. The number of patterns and the number of mirrors deleted were negatively correlated. The number of new features was negatively correlated to the percentage retention and the number of features changed or retained. As more features were deleted, new ones were created to replace the deleted features. The number of features changed was positively correlated with the proxy ratings (though only statistically significant for intuitive order). A well-organized model with ordered features was easier to modify. Models which received higher ratings for the intuitive ordering of features were rated higher on organization and overall quality which could be expected.

Engineers that ensured proper order also ensured good organization and a model that would be perceived as easier to work with.

6.3. Comparison with Parent Models

Paired t-test analyses were carried out to compare the attributes of the parent and altered models and the results are tabulated in Table 19 and Table 20. These comparisons are used to examine the alteration process of the models. It should be noted that the averages for the parent model attributes listed in Table 19 and Table 20 will be different from those listed in Table 15 and Table 17. This is because these averages pertain only to the parent models and not the entire set of original models as listed in Table 15 and Table 17.

6.3.1. Parent Models Designed for Speed

Table 19- Comparison of Model Attributes between Altered Models and Parent Models (Incentivized for Speed in Set 2)

Model Attribute	Parent	Altered	Mean Difference	t	Sig (1-tailed)*
No. of Features	11.40	15.07	-3.67	-6.381	**0.000**
Reference Geometry Features	0.20	0.47	-0.27	-1.740	**0.052**
Average No. of Segments	6.77	4.42	2.35	4.133	**0.001**
Total Weak Dimensions	0.00	0.47	-0.47	-1.974	**0.034**
Incorrect Feature Terminations	0.40	0.80	-0.40	-1.572	**0.069**
No. of Mirror Features	2.00	1.60	0.40	0.972	0.174
No. of Pattern Features	1.00	0.67	0.33	1.435	**0.087**
Traditional Feature Sequence	0.40	0.20	0.20	1.000	0.167

* $\alpha = 0.100$

The number of features increased significantly in the altered models. This was expected, since there were features in the altered design which had to replace existing ones (e.g., chamfers replaced rounds). The parent models had more reference geometry features and segments on an average. The introduction of newer features during alteration and the addition of simpler features catering only to the changes, contributed to this reduction. Though there were more weak dimensions in the altered designs there were only 4 engineers who contributed to this. There were also significantly more incorrect feature terminations in the altered models. The number of mirrors and patterns were reduced in the altered models, though the difference was not statistically significant in the case of the number of mirrors. This was influenced by the design provided for alteration.

6.3.2. Parent Models Designed for Ease of Alteration

Table 20 – Comparison of Model Attributes between Altered Models and Parent Models (Incentivized for Ease of Alteration in Set 2)

Model Attribute	Parent	Altered	Mean Difference	t	Sig (1-tailed)*
No Of Features	11.80	15.33	-3.53	-12.909	**0.000**
Reference Geometry Features	0.20	0.60	-0.40	-3.055	**0.004**
Average No. of Segments	5.59	4.21	1.39	7.905	**0.000**
Total Weak Dimensions	0.00	0.53	-0.53	-1.835	**0.044**
Incorrect Feature Terminations	0.00	0.13	-0.13	-1.468	**0.082**
No. of Mirror Features	2.80	1.67	1.13	4.795	**0.000**
No. of Pattern Features	1.20	0.53	0.67	3.568	**0.002**
Traditional Feature Sequence	1.00	0.60	0.40	3.055	**0.004**

* $\alpha = 0.100$

In the models incentivized for ease of alteration, there were significantly more features and reference geometry features in the altered models. The average number of segments was reduced, similar to the case for those incentivized for speed. There was an increase in the number of weak dimensions and incorrect feature terminations in the altered models. Weak dimensions arose during sketch modifications or cut features which were larger than the required sketch size. There were fewer mirrors and patterns in the modified models. This was influenced by the design to which the parent model was altered. Traditional feature sequence was also compromised during alteration. Features added during alteration were added to the end of the model tree thus affecting the sequence.

CHAPTER VII

DISCUSSION AND CONCLUSIONS

In this chapter the results of the preceding three sections are summarized and compared. The results of the surveys on how the inclusion of a certain type of feature and model attributes to the parent model would have affected the ease of alteration and perception of the model are also compared. Conclusions are drawn based on these results.

7.1. Summary of Results

The important results from Chapters IV, V and VI are summarized below.

7.1.1. Results from Junior Level CAD Course

Group 1B, incentivized to create the models for ease of alteration, required more time for model creation; however the difference was not statistically significant. The differences between the number of features and the number of weak dimensions were not statistically significant. Group 1B participants used significantly more mirror features and fewer pattern features. Modeling time was positively correlated with the number of features and negatively correlated with the average number of segments; it would be quicker to create models with a few complex features. However, the differences were not statistically significant.

The alteration time for models that were created for the ease of alteration was significantly less than those created for speed. Models created for alteration had significantly more features; significantly more features were altered, and the percentage of features retained was significantly higher. The design intent proxy ratings were also statistically significantly greater for models created for ease of alteration. Models with more weak dimensions required more time to alter as indicated by the positive correlation; however, the correlation was not statistically significant. There was a statistically significant positive correlation between alteration time and the number of mirror features. Parent models that were rated high on intuitive order and organization had a high percentage of features retained and a high number of features changed. Models with features that were poorly ordered and organized were hard to alter; this was indicated by the significant negative correlation between alteration time and the corresponding proxy ratings.

Comparing the altered model attributes with those of the parent models, it was seen that the number of features increases significantly during alteration if the parent models were created using a few complex features. There was also a significant increase in the number of weak dimensions in the models created for ease of alteration.

7.1.2. Results from Senior Level CAD Course

The group incentivized to create models for the ease of alteration (Group 2B) required more time for model creation; however, the difference was not statistically significant. There was approximately the same number of features used by both groups during model creation. The modeling time was not affected by the number of features or the complexity of the features; these could be seen from the correlations which were not statistically significant.

Models created for the ease of alteration required slightly less time for alteration; the difference was not statistically significant. All the design intent proxy ratings, except that for intuitive organization were significantly greater for the models created for ease of alteration. The intuitive organization ratings were also greater, however, not statistically significant. Models with fewer, more complex features required significantly less time for alteration. Models with more weak dimensions required significantly more time for alteration. As expected, parent models that were difficult to alter received low design intent proxy ratings. Models with more weak dimensions were hard to be perceived; this was also reflected in the lower ratings. Models that received high design intent proxy ratings had a high percentage of features retained and a high number of features changed.

Comparing the attributes of the altered models with those of the parent models, it was found that there was a significant increase in the number of features and a significant decrease in the average number of segments during alteration. During alteration, there was a significant increase in the number of weak dimensions.

7.1.3. Results from Experienced Engineers

The modeling time taken by the group incentivized for creating models for the ease of alteration (Group 3B) was significantly greater. There were no model attributes that were statistically significantly different between the different incentive groups. Modeling time was significantly negatively correlated with the experience of the participant. Consistent with the claim of Hamade, et al., there was a significant negative correlation between the average number of segments and the modeling time [41]; complex features required less time for creation.

Both the groups required approximately the same time for alteration. There was a significant difference in maintaining the traditional feature sequence during alteration; the group altering models that were created for the ease of alteration had more models with the traditional feature sequence. There was no significant difference between the design intent proxy ratings. Models with more weak dimensions required significantly more time for alteration. Though all the design intent proxy ratings were negatively correlated with alteration time, only the overall rating was statistically significantly correlated. The number of features was positively correlated with all the design intent proxy ratings indicating that with more features, the model could be perceived well; only the intuitive organization rating was significantly correlated. The number of mirrors was significantly negatively correlated with intuitive organization while the number of patterns was significantly positively correlated; patterns helped in better organization while mirrors were detrimental to organization.

Comparing attributes of altered models with those of parent models, a significant increase in the number of features, the number of weak dimensions and a significant reduction in the percentage of models with the traditional feature sequence were noticed.

7.2. Comparison of Attributes of Models Created for Speed

One way ANOVA test was used to compare the three different sets of data and assess if there was a significant difference between the variables. To further understand which sample mean(s) was/were significantly different from the others the Tukey's HSD test was used. One tailed probability is used in the analyses due to the unidirectional relevance of the quantities in relation to the expected results. It should be noted that Set 1 refers to the data from the junior level CAD course (using Pro|Engineer), Set 2 refers to the data from the senior level CAD course (using Solidworks) and Set 3 refers to the data from the experienced engineers (using Pro|Engineer). As explained earlier, the similarities between the two CAD packages as far as the features, sketch entities and sketch manipulation options are evidence for the validity of this comparison.

Table 21 – Comparison of Attributes of Models Created for Speed by the Three Sets of Participants

	F	Sig.*
Time	20.311	**0.000**
Sketch Plane	6.704	**0.002**
Orientation	3.333	**0.043**
No of Features	8.629	**0.001**
Reference Geometry	1.114	0.336
Average no. of Segments	7.091	**0.002**
Total Weak Dimensions	4.827	**0.012**
Incorrect Feature Term.	3.385	**0.041**
No. of Mirror Features	6.880	**0.002**
No. of Pattern Features	13.022	**0.000**
Correct Feature Seq.	23.300	**0.000**

*$\alpha=0.100$

Table 21 summarizes the results of the one way ANOVA test for the comparison of means of the variables from the three sets of data. The participants were Group 1A, Group 2A and Group 3A who were incentivized for creating the models as quickly as possible. There was no difference only in the number of reference geometry used by the three sets of participants.

Table 22 – Tukey's HSD Test for Comparison of the Attributes of Models Created for Speed by the Three Sets of Participants

	Group (I)	Group (J)	Mean (I)	Mean (J)	Mean Difference (I-J)	Sig. (1-tailed)*
Time	1A	2A	35.35	29.52	5.831	**0.045**
	1A	3A	35.35	16.64	18.710	**0.000**
	2A	3A	29.52	16.64	12.879	**0.000**
Sketch Plane	1A	2A	0.91	0.85	0.063	0.427
	1A	3A	0.91	0.47	0.446	**0.001**
	2A	3A	0.85	0.47	0.383	**0.007**
Orientation	1A	2A	0.74	0.85	-0.111	0.346
	1A	3A	0.74	0.47	0.272	**0.080**
	2A	3A	0.85	0.47	0.383	**0.018**
No. of Features	1A	2A	16.39	12.15	4.241	**0.001**
	1A	3A	16.39	12.33	4.058	**0.003**
	2A	3A	12.15	12.33	-0.183	0.494
Reference Geometry	1A	2A	0.87	1.40	-0.530	0.208
	1A	3A	0.87	0.80	0.070	0.494
	2A	3A	1.40	0.80	0.600	0.203
Average no. of Segments	1A	2A	3.70	5.59	-1.899	**0.004**
	1A	3A	3.70	5.85	-2.152	**0.003**
	2A	3A	5.59	5.85	-0.253	0.463
Total Weak Dimensions	1A	2A	4.78	5.35	-0.567	0.462
	1A	3A	4.78	0.53	4.249	**0.015**
	2A	3A	5.35	0.53	4.817	**0.008**
Incorrect Feature Term.	1A	2A	0.91	0.85	0.063	0.477
	1A	3A	0.91	0.33	0.580	**0.022**
	2A	3A	0.85	0.33	0.517	**0.046**
No. of Mirror Features	1A	2A	2.35	0.35	1.998	**0.003**
	1A	3A	2.35	2.47	-0.119	0.491
	2A	3A	0.35	2.47	-2.117	**0.004**
No. of Pattern Features	1A	2A	2.17	0.20	1.974	**0.000**
	1A	3A	2.17	0.80	1.374	**0.003**
	2A	3A	0.20	0.80	-0.600	0.187
Traditional Feature Sequence	1A	2A	0.00	0.00	0.000	0.500
	1A	3A	0.00	0.53	-0.533	**0.000**
	2A	3A	0.00	0.53	-0.533	**0.000**

α=0.100

The results presented in Table 22 are summarized below. The average times taken by the three sets of participants, who were incentivized to create models as quickly as possible, were significantly different. As expected, the professionals required the least amount of time followed by the participants from senior level CAD course. The models from Group 1A participants had the significantly more of features compared to the other two sets; the difference between the number of features of models from Group 2A and Group 3A participants was not statistically significant. Group 3A models had significantly fewer weak dimensions and incorrectly terminated features compared to those from Group 1A and Group 2A. Group 1A and Group 3A models had significantly more mirror features compared to Group 2A models. It should be noted however that Group 1A models had predominantly mirror features as opposed to Group 3A models which predominantly had sketched mirrors. Group 1A models had significantly more pattern features while there was no statistically significant difference between the number of patterns in models created by Group 2A and Group 3A participants. Only Group 3A participants had ordered their features in the correct sequence.

7.3. Comparison of Attributes of Models Created for Ease of Alteration

Unlike the Group 1A, 2A and 3A models, in Group 1B, 2B, 3B models (incentivized for the ease of alteration) there was no difference between the sketch planes and orientation chosen by the participants. These results are summarized in Table 23. To further understand which variables were significantly different, the results of the Tukey's HSD test are analyzed. The results of the Tukey's HSD test are presented in Table 24.

Table 23 – Comparison of Attributes Models Created for Ease of Alteration by the Three Sets of Participants

	F	Sig.
Time	19.498	**0.000**
Sketch Plane	0.745	0.480
Orientation	0.002	0.998
No of Features	17.514	**0.000**
Reference Geometry	2.495	**0.093**
Average no. of Segments	20.877	**0.000**
Total Weak Dimensions	6.257	**0.004**
Incorrect Feature Term.	3.816	**0.029**
No. of Mirror Features	9.893	**0.000**
No. of Pattern Features	4.570	**0.015**
Correct Feature Seq.	35.849	**0.000**

$*\alpha=0.100$

The modeling times for Groups 1B, 2B and 3B were significantly different from each other as in the case of Groups 1A, 2A and 3A; the trend in the modeling times was also similar with Group 3B taking lesser time than Group 2B which in turn required lesser time than Group 1B. But Group 1B models had significantly more features than Group 2B and Group 3B models; the difference between the number of features in models created by Group 2B and 3B participants were not statistically significant. Group 2B models had significantly more weak dimensions and significantly fewer mirror features compared to Group 1B and Group 3B models. Among the groups incentivized for ease of alteration only the Group 3B (experienced engineers) had ensured that the features were created in the correct sequence; the difference from the other groups was statistically significant.

Table 24 – Tukey's HSD Test for Comparison of Attributes of Models Created for Ease of Alteration by the Three Sets of Participants

	Group (I)	Group (J)	Mean (I)	Mean (J)	Mean Difference (I-J)	Sig. (1-tailed)
Time	1B	2B	39.00	33.02	5.988	**0.055**
	1B	3B	39.00	20.85	18.150	**0.000**
	2B	3B	33.02	20.85	12.162	**0.001**
Sketch Plane	1B	2B	0.78	0.67	0.116	0.367
	1B	3B	0.78	0.60	0.183	0.235
	2B	3B	0.67	0.60	0.067	0.459
Orientation	1B	2B	0.61	0.60	0.009	0.499
	1B	3B	0.61	0.60	0.009	0.499
	2B	3B	0.60	0.60	0.000	0.500
No. of Features	1B	2B	17.61	12.27	5.342	**0.000**
	1B	3B	17.61	12.73	4.875	**0.000**
	2B	3B	12.27	12.73	-0.467	0.456
Reference Geometry	1B	2B	1.26	1.53	-0.272	0.399
	1B	3B	1.26	0.53	0.728	0.105
	2B	3B	1.53	0.53	1.000	**0.046**
Average no. of Segments	1B	2B	3.02	6.04	-3.025	**0.000**
	1B	3B	3.02	5.14	-2.124	**0.000**
	2B	3B	6.04	5.14	0.901	0.116
Total Weak Dimensions	1B	2B	3.91	11.07	-7.154	**0.022**
	1B	3B	3.91	0.00	3.913	0.187
	2B	3B	11.07	0.00	11.067	**0.002**
Incorrect Feature Term.	1B	2B	1.17	0.73	0.441	0.216
	1B	3B	1.17	0.20	0.974	**0.011**
	2B	3B	0.73	0.20	0.533	0.181
No. of Mirror Features	1B	2B	3.35	0.67	2.681	**0.000**
	1B	3B	3.35	3.13	0.214	0.470
	2B	3B	0.67	3.13	-2.467	**0.001**
No. of Pattern Features	1B	2B	1.65	0.27	1.386	**0.006**
	1B	3B	1.65	0.93	0.719	0.137
	2B	3B	0.27	0.93	-0.667	0.198
Traditional Feature Sequence	1B	2B	0.00	0.00	0.000	0.500
	1B	3B	0.00	0.67	-0.667	**0.000**
	2B	3B	0.00	0.67	-0.667	**0.000**

**α=0.100*

A graphical comparison of the results (from the first phase) for some of the key attributes has been presented below.

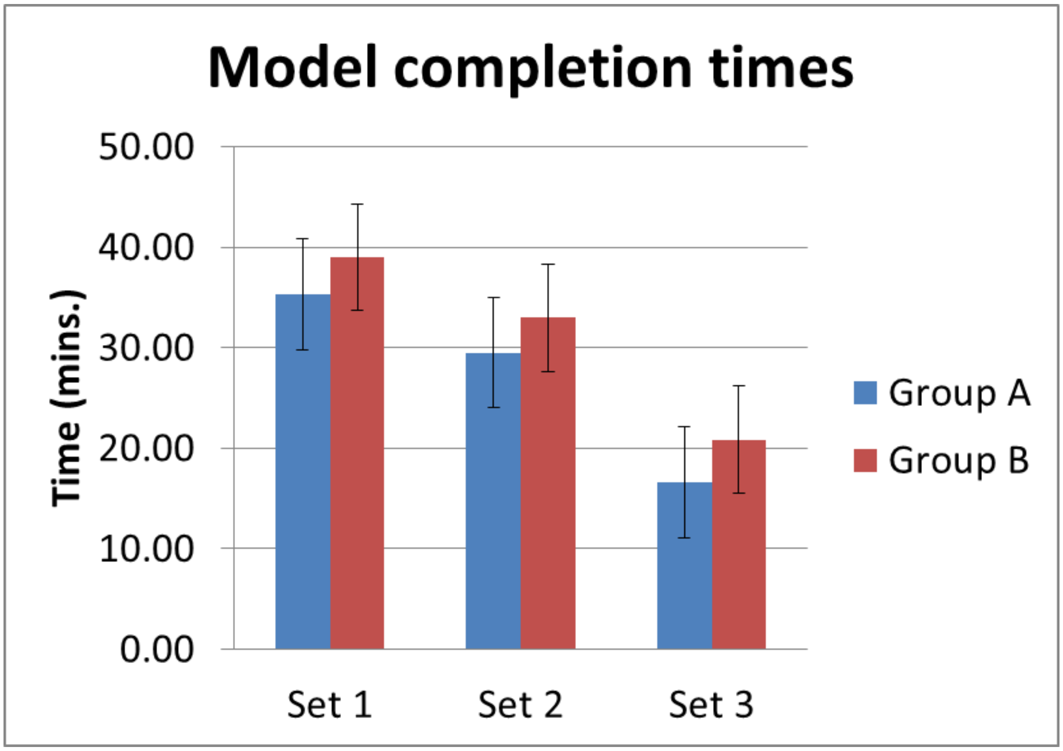

Figure 7 – Comparison of model creation times in the first phase

The model creation times for the incentive groups of the three sets are shown in Figure 7. It should be noticed that with the increase in experience with the CAD package, the model creation time reduced. Also, participants incentivized for the ease of alteration took more time for model creation as one would expect.

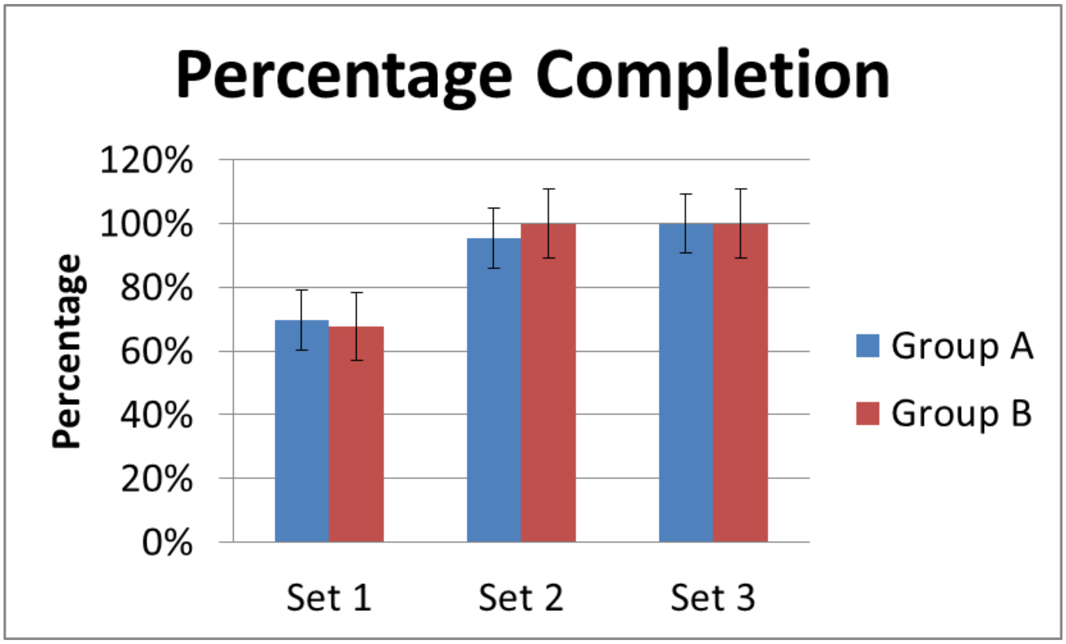

Figure 8 – Comparison of the percentage of participants completing the first phase

A comparison of the percentage of participants who completed the modeling task in the first phase is shown in Figure 8. With experience, the number of participants completing the exercise increased. All participants in Set 3 (experienced engineers) were able to complete the exercise.

Figure 9 shows a comparison between the numbers of features used to create models by the three sets of participants. Set 1 engineers used the maximum number of features for model creation. This could be attributed to the skill level of the participants – they were not aware of the several alternate ways of creating the model and adhered to simple sketched geometry resulting in a very high feature count.

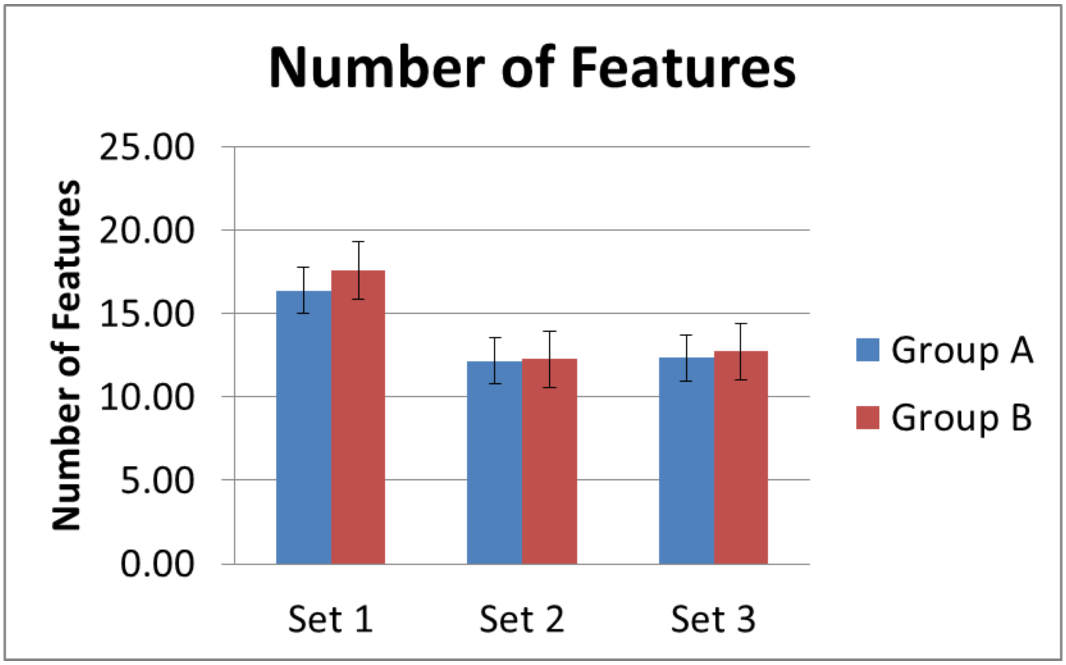

Figure 9 – Comparison of the number of features in models from the first phase

Figure 10 shows a comparison between the average numbers of segments per feature during model creation by the three sets of participants. Consistent with the number of features used, the average number of segments was low for Set 1 – use of more features would result in a lower average number of segments per feature. Set 2 had slightly more segments compared to Set 3 and this was because fillet and chamfer features were predominantly sketched rather than created as independent features; this was a common practice observed with Set 2 participants.

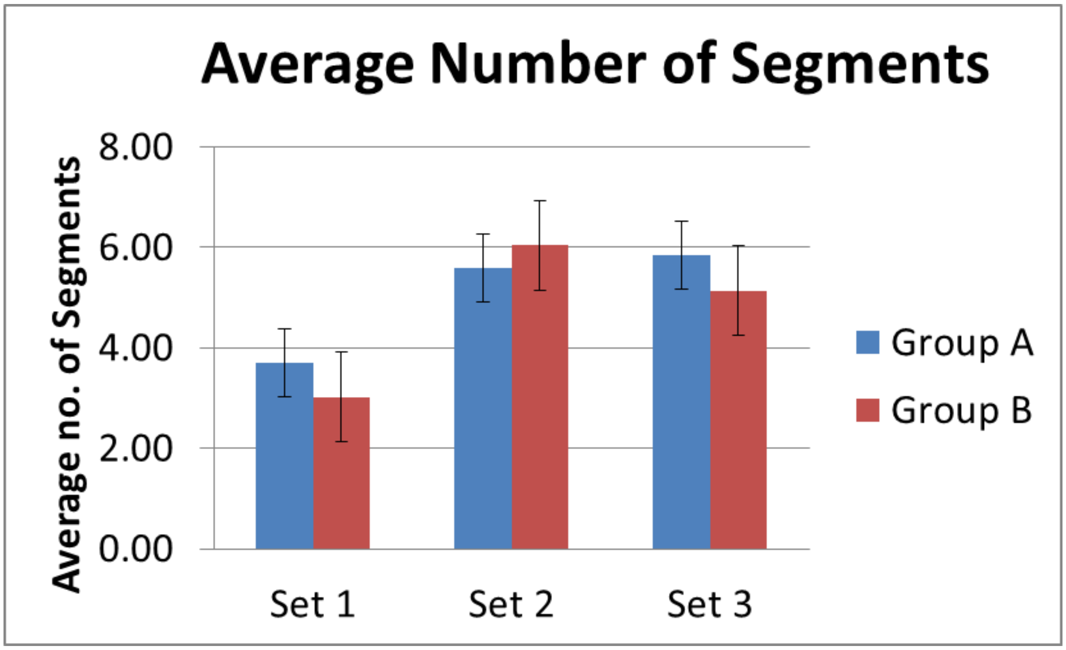

Figure 10 – Comparison of the average number of segments between models from the first phase

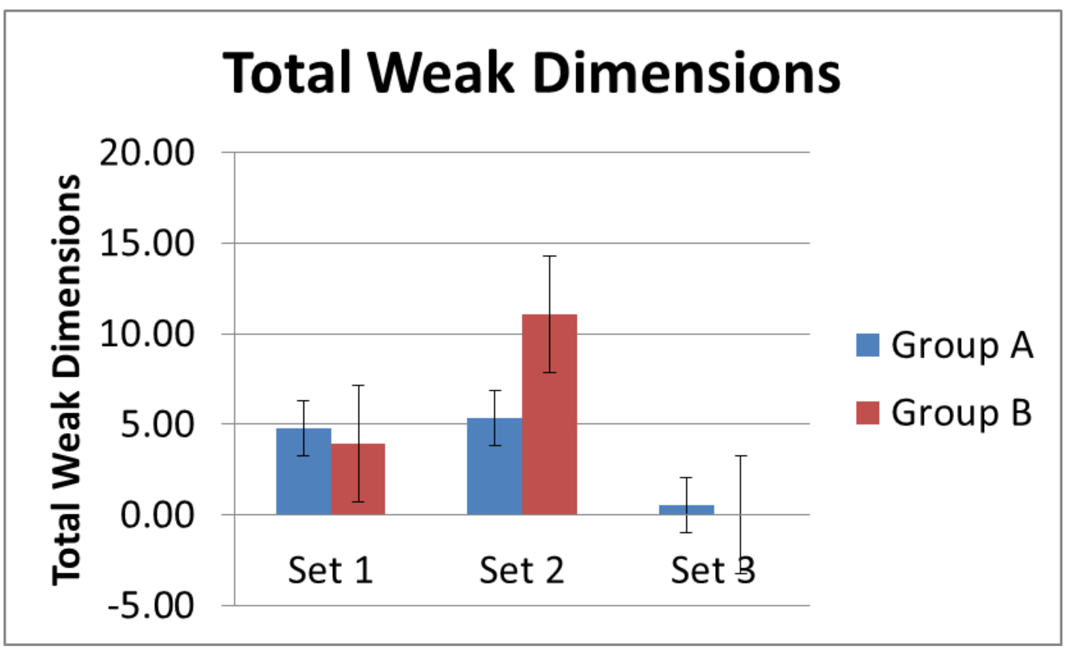

Figure 11 – Comparison of the number of weak dimensions in models from the first phase

Weak dimensions which are detrimental to a model were avoided by the experienced engineers. This can be seen from Figure 11. Set 2 models had more weak dimensions than Set 1 models; this could be attributed to the way weak dimensions are handled by the CAD package used by Set 2 participants (Solidworks). Unlike in Pro|Engineer, Solidworks does not explicitly display weak dimensions for the participants to be able to convert them to strong ones and have the sketches completely constrained.

The numbers of features incorrectly terminated in the models created by the three sets of participants are compared in Figure 12. The number of features that were incorrectly terminated reduced with experience. Also, participants incentivized for ease of alterations took extra care to terminate features correctly. Surprisingly this was not the case with Set 1 participants where more features from Group 1B models were incorrectly terminated.

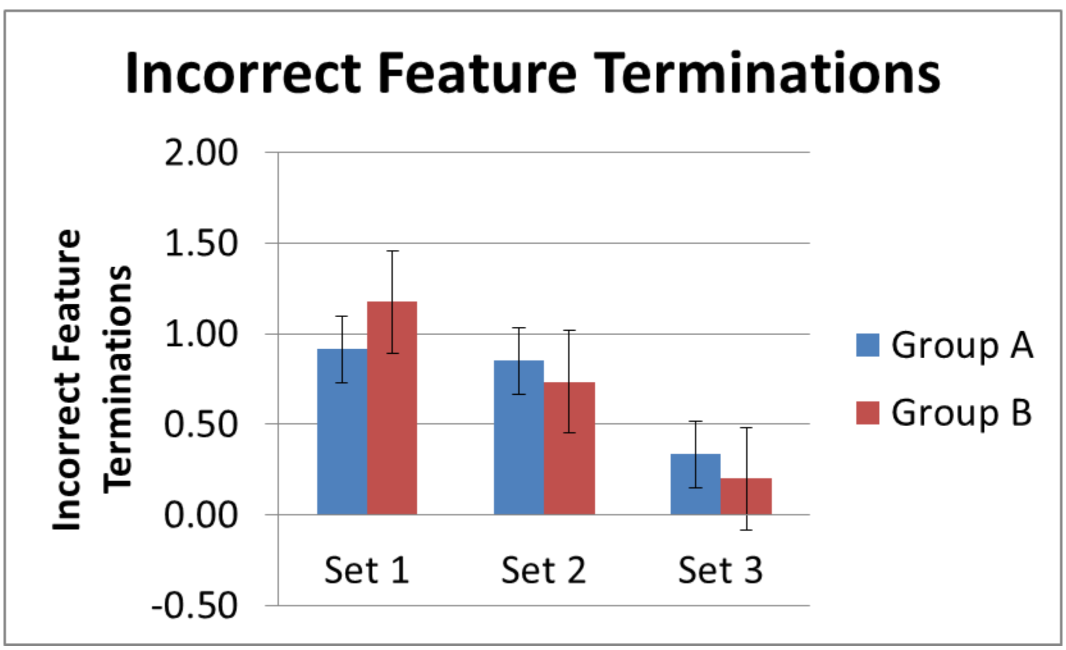

Figure 12 – Comparison of incorrect feature terminations in models from the first phase

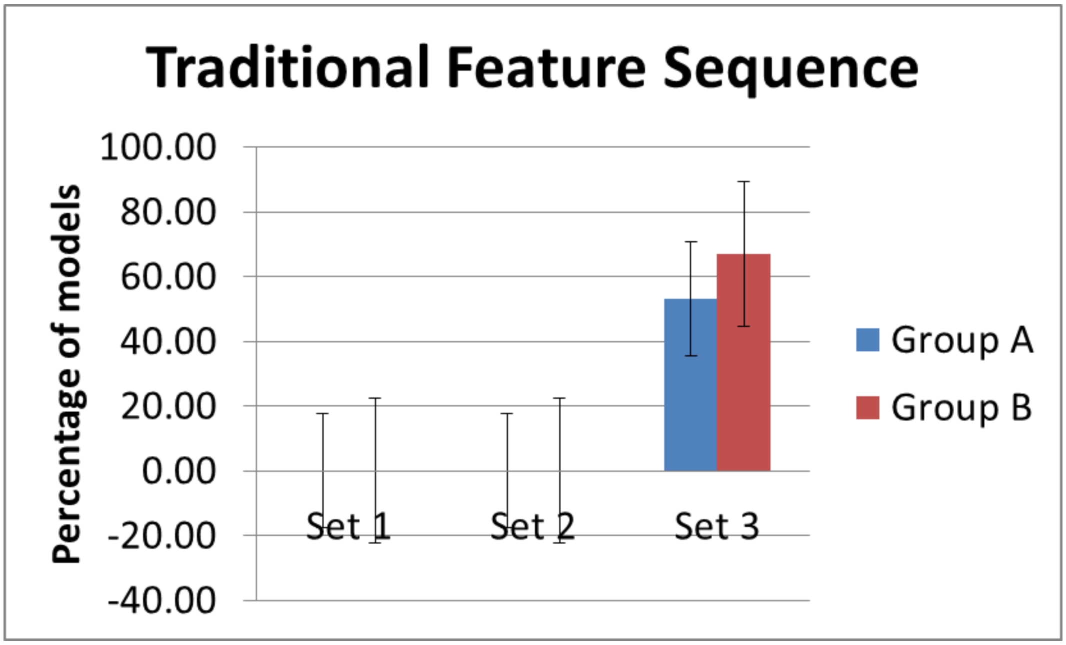

Figure 13 – Comparison of the percentage of models with the traditional feature sequence followed in models from the first phase

Figure 13 shows a comparison between the percentages of models with the traditional feature sequence. Only practicing engineers had maintained the traditional feature sequence in the models created (Figure 13). This could be attributed to the industry experience gained by the practicing professionals.

7.4. Comparison of Attributes of Altered Models (Parent Models Created for Speed)

Table 25 – Comparison of Attributes of Models Altered by the Three Sets of Participants (Parent Models Created for Speed)

	F	Sig.*
Change Time	33.244	**0.000**
Sketch Plane	10.697	**0.000**
Orientation	4.977	**0.011**
No. of Features	12.540	**0.000**
Reference Geometry	2.684	**0.079**
Average no. of Segments	19.697	**0.000**
Total Weak Dimensions	10.915	**0.000**
Incorrect Feature Term.	0.529	0.593
No. of Mirror Features	7.020	**0.002**
No. of Pattern Features	4.874	**0.012**
Traditional Feature Sequence	3.867	**0.028**
No. of New Features	3.568	**0.036**
No. of Features Deleted	6.409	**0.004**
% Retention	3.440	**0.041**
No. Retained w/o change	2.121	0.132
No. of Features Changed	2.165	0.127
New Patterns	0.346	0.709
New Mirrors	1.906	0.161
No. of Mirrors Deleted	3.697	**0.033**
No. of Patterns Deleted	1.288	0.286
Intuitive Organization	3.413	**0.042**
Intuitive Order	4.448	**0.017**
Overall	2.100	0.134

α=0.100

Groups 1B, 2B and 3B were the participants in the alteration exercise where the parent models where created for speed. There was a statistically significant difference between several attributes and derived parameters of the altered models from the different groups of participants. The results of the one-way ANOVA test on the variables and the corresponding statistic are shown in Table 25. To further understand the difference between the groups, the results of the Tukey's HSD test were studied. The results are presented in Table 26.

Table 26 – Tukey's HSD Test for Comparison of Attributes of Altered Models (Parent Models Created for Speed)

	Group (I)	Group (J)	Mean (I)	Mean (J)	Mean Diff. (I-J)	Sig. (1-tailed)*
Alteration Time	1B	2B	43.03	35.33	7.698	**0.014**
	1B	3B	43.03	18.98	24.045	**0.000**
	2B	3B	35.33	18.98	16.346	**0.000**
Sketch Plane	1B	2B	1.00	0.83	0.167	0.203
	1B	3B	1.00	0.40	0.600	**0.000**
	2B	3B	0.83	0.40	0.433	**0.002**
Orientation	1B	2B	0.87	0.78	0.089	0.414
	1B	3B	0.87	0.40	0.467	**0.007**
	2B	3B	0.78	0.40	0.378	**0.021**
No. of Features	1B	2B	17.73	14.17	3.567	**0.000**
	1B	3B	17.73	15.07	2.667	**0.002**
	2B	3B	14.17	15.07	-0.900	0.220
Reference Geometry	1B	2B	1.27	1.06	0.211	0.407
	1B	3B	1.27	0.47	0.800	**0.039**
	2B	3B	1.06	0.47	0.589	0.106
Average no. of Segments	1B	2B	3.53	5.28	-1.741	**0.000**
	1B	3B	3.53	4.42	-0.888	**0.005**
	2B	3B	5.28	4.42	0.853	**0.005**
Total Weak Dimensions	1B	2B	4.07	8.28	-4.211	**0.021**
	1B	3B	4.07	0.47	3.600	**0.056**
	2B	3B	8.28	0.47	7.811	**0.000**
Incorrect Feature Term.	1B	2B	0.53	0.56	-0.022	0.498
	1B	3B	0.53	0.80	-0.267	0.316
	2B	3B	0.56	0.80	-0.244	0.329
No. of Mirror Features	1B	2B	1.73	0.33	1.400	**0.002**
	1B	3B	1.73	1.60	0.133	0.475
	2B	3B	0.33	1.60	-1.267	**0.006**

Table 26 continued

	Group (I)	**Group (J)**	**Mean (I)**	**Mean (J)**	**Mean Diff. (I-J)**	**Sig. (1-tailed)***
No. of Pattern Features	1B	2B	0.53	0.06	0.478	**0.034**
	1B	3B	0.53	0.67	-0.133	0.407
	2B	3B	0.06	0.67	-0.611	**0.007**
Traditional Feature Sequence	1B	2B	0.00	0.00	0.000	0.500
	1B	3B	0.00	0.20	-0.200	**0.028**
	2B	3B	0.00	0.20	-0.200	**0.022**
No. of New Features	1B	2B	9.87	7.22	2.644	**0.025**
	1B	3B	9.87	7.33	2.533	**0.039**
	2B	3B	7.22	7.33	-0.111	0.497
No. of Features Deleted	1B	2B	7.47	4.67	2.800	**0.016**
	1B	3B	7.47	3.60	3.867	**0.002**
	2B	3B	4.67	3.60	1.067	0.292
% Retention	1B	2B	48.51	59.72	-11.206	0.147
	1B	3B	48.51	68.75	-20.242	**0.016**
	2B	3B	59.72	68.75	-9.036	0.224
No. of Features Retained w/o Change	1B	2B	2.20	1.61	0.589	0.335
	1B	3B	2.20	0.73	1.467	**0.057**
	2B	3B	1.61	0.73	0.878	0.207
No. of Features Changed	1B	2B	5.60	5.11	0.489	0.434
	1B	3B	5.60	7.07	-1.467	0.161
	2B	3B	5.11	7.07	-1.956	**0.059**
New Patterns	1B	2B	0.13	0.06	0.078	0.357
	1B	3B	0.13	0.07	0.067	0.398
	2B	3B	0.06	0.07	-0.011	0.497
New Mirrors	1B	2B	0.47	0.00	0.467	**0.094**
	1B	3B	0.47	0.40	0.067	0.484
	2B	3B	0.00	0.40	-0.400	0.145
No. of Mirrors Deleted	1B	2B	0.87	0.11	0.756	**0.025**
	1B	3B	0.87	0.80	0.067	0.489
	2B	3B	0.11	0.80	-0.689	**0.041**
No. of Patterns Deleted	1B	2B	0.93	0.44	0.489	0.183
	1B	3B	0.93	0.40	0.533	0.167
	2B	3B	0.44	0.40	0.044	0.496
Intuitive Organization	1B	2B	3.80	4.41	-0.608	0.199
	1B	3B	3.80	5.07	-1.267	**0.016**
	2B	3B	4.41	5.07	-0.659	0.170
Intuitive Order	1B	2B	3.91	4.59	-0.681	0.102
	1B	3B	3.91	5.13	-1.222	**0.006**
	2B	3B	4.59	5.13	-0.541	0.181
Overall	1B	2B	4.03	4.15	-0.114	0.481
	1B	3B	4.03	4.87	-0.833	**0.079**
	2B	3B	4.15	4.87	-0.719	0.111

*$\alpha=0.100$

During the alteration of parent models which were created for speed, the alteration time was significantly different for all three groups of participants. The trend was the same as in the previous cases. Group 1B participants had used a significantly more number of features than Groups 2B and 3B. There were significant differences between the groups in the average number of segments and the total number of weak dimensions. Group 2B models had maximum number of segments per feature (5.28) followed by Group 3B models (4.42) and Group 1B models (3.53); the differences between the groups was statistically significant. Group 2B models had 8.28 weak dimensions per model while Group 1B models had less than half the number of weak dimensions (4.07). Group 3B models had only 0.47 weak dimensions per model. The differences between the groups were statistically significant. Interestingly, the differences between the groups in the way features were terminated were not statistically significant. Group 2B had significantly fewer mirror and pattern features compared to Groups 1B and 3B. Though only 20% of the models from Group 3B had the traditional feature sequence, the differences against the other Groups were statistically significant because there were no models with the traditional feature sequence in the other groups. Significantly more features had to be deleted by Group 1B participants during alteration. Though Group 3B participants managed to change the greatest number of features during alteration, the difference was significant only when compared to Group 1B models; the difference was not statistically significant with the number of features changed in Group 2B models. Group 3B models received the best intuitive order, intuitive organization and overall ratings when compared to Group 1B models. Group 3B models received higher ratings than Group 2B models; however the difference was not statistically significant.

7.5. Comparison of Attributes of Altered Models (Parent Models Created for Ease of Alteration)

Table 27 – Comparison of Attributes of Models Altered by the Three Sets of Participants (Parent Models Created for Ease of Alteration)

	F	**Sig.***
Change Time	13.786	**0.000**
Sketch Plane	0.853	0.432
Orientation	1.290	0.284
No. of Features	4.078	**0.023**
Reference Geometry	5.755	**0.006**
Average no. of Segments	11.345	**0.000**
Total Weak Dimensions	9.545	**0.000**
Incorrect Feature Term.	2.984	**0.060**
No. of Mirror Features	2.681	**0.079**
No. of Pattern Features	4.858	**0.012**
Traditional Feature Sequence	1.154	0.324
No. of New Features	16.815	**0.000**
No. of Features Deleted	4.288	**0.019**
% Retention	4.195	**0.021**
No. Retained w/o change	4.248	**0.020**
No. of Features Changed	0.421	0.658
New Patterns	2.746	**0.074**
New Mirrors	4.968	**0.011**
No. of Mirrors Deleted	10.706	**0.000**
No. of Patterns Deleted	1.523	0.228
Intuitive Organization	3.612	**0.034**
Intuitive Order	3.615	**0.034**
Overall	26.149	**0.000**

*α=0.100

Table 28 lists the differences between the various attributes and derived parameters of models altered by Groups 1A, 2A and 3A which were created for the ease of alteration. While the time taken to alter the models by Group 1A and 2A participants were not statistically significantly different, Group 3A participants were significantly quicker in alteration. Group 3A models also had significantly fewer features when compared to Group 1A models. The differences between the average numbers of segments in the models from the groups were statistically significant. Group 1A, 2A and 3A models had 18.9, 16.75 and 15.33 features respectively. Group 2A models had the highest number of segments per feature (4.85), followed by Group 3A (4.21) and then by Group 1A (3.44). Group 3A models again had the lowest number of weak dimensions (0.53) significantly different from those of Group 2A (8.44) and Group 1A (3.67); the differences between the groups were statistically significant. Group 1A models had the lowest number of features retained and the difference was statistically significant. Group 2A models had the lowest number of features that were modified (5.06) during alteration; this was significantly different from those of Group 1A (6.43) and Group 3A (7.33). Models from all three groups received approximately the same ratings for intuitive organization; the differences were not statistically significant. However, parent models altered by Group 1A models received statistically significantly lower ratings for intuitive order when compared to models altered by Group 2A and Group 3A. Overall ratings received by Group 1A and Group 3A parent models were statistically significantly different.

Table 28 – Tukey's HSD Test for Comparison of Attributes of Altered Models (Parent Models Created for Ease of Alteration)

	Group (I)	Group (J)	Mean (I)	Mean (J)	Mean Difference (I-J)	Sig. (1-tailed)*
Alteration Time	1A	2A	35.42	34.39	1.032	0.476
	1A	3A	35.42	18.23	17.186	**0.000**
	2A	3A	34.39	18.23	16.154	**0.000**
Sketch Plane	1A	2A	0.67	0.82	-0.146	0.309
	1A	3A	0.67	0.60	0.067	0.453
	2A	3A	0.82	0.60	0.213	0.211
Orientation	1A	2A	0.57	0.81	-0.241	0.145
	1A	3A	0.57	0.60	-0.029	0.491
	2A	3A	0.81	0.60	0.213	0.218
No. of Features	1A	2A	18.90	16.75	2.155	0.104
	1A	3A	18.90	15.33	3.571	**0.010**
	2A	3A	16.75	15.33	1.417	0.277
Reference Geometry	1A	2A	2.14	2.44	-0.295	0.425
	1A	3A	2.14	0.60	1.543	**0.010**
	2A	3A	2.44	0.60	1.838	**0.004**
Average no. of Segments	1A	2A	3.44	4.85	-1.412	**0.000**
	1A	3A	3.44	4.21	-0.771	**0.019**
	2A	3A	4.85	4.21	0.641	**0.064**
Total Weak Dimensions	1A	2A	3.67	8.44	-4.771	**0.009**
	1A	3A	3.67	0.53	3.133	**0.087**
	2A	3A	8.44	0.53	7.904	**0.000**
Incorrect Feature Term.	1A	2A	0.48	0.50	-0.024	0.494
	1A	3A	0.48	0.13	0.343	**0.046**
	2A	3A	0.50	0.13	0.367	**0.045**
No. of Mirror Features	1A	2A	1.38	0.63	0.756	0.100
	1A	3A	1.38	1.67	-0.286	0.398
	2A	3A	0.63	1.67	-1.042	**0.039**
No. of Pattern Features	1A	2A	1.00	0.13	0.875	**0.004**
	1A	3A	1.00	0.53	0.467	0.123
	2A	3A	0.13	0.53	-0.408	0.191
Traditional Feature Sequence	1A	2A	0.00	0.00	0.000	0.500
	1A	3A	0.00	0.60	-0.600	**0.000**
	2A	3A	0.00	0.60	-0.600	**0.000**
No. of New Features	1A	2A	9.14	13.44	-4.295	0.285
	1A	3A	9.14	6.60	2.543	0.413
	2A	3A	13.44	6.60	6.838	0.151
No. of Features Deleted	1A	2A	9.10	3.31	5.783	**0.000**
	1A	3A	9.10	3.20	5.895	**0.000**
	2A	3A	3.31	3.20	0.113	0.498

Table 28 continued

	Group (I)	Group (J)	Mean (I)	Mean (J)	Mean Difference (I-J)	Sig. (1-tailed)*
% Retention	1A	2A	53.93	68.23	-14.297	**0.048**
	1A	3A	53.93	72.67	-18.739	**0.012**
	2A	3A	68.23	72.67	-4.441	0.408
No. of Features Retained w/o Change	1A	2A	3.29	3.56	-0.277	0.469
	1A	3A	3.29	1.27	2.019	**0.023**
	2A	3A	3.56	1.27	2.296	**0.015**
No. of Features Changed	1A	2A	6.43	5.06	1.366	**0.078**
	1A	3A	6.43	7.33	-0.905	0.223
	2A	3A	5.06	7.33	-2.271	**0.008**
New Patterns	1A	2A	0.19	0.13	0.065	0.438
	1A	3A	0.19	0.07	0.124	0.318
	2A	3A	0.13	0.07	0.058	0.457
New Mirrors	1A	2A	0.38	0.00	0.381	**0.045**
	1A	3A	0.38	0.07	0.314	**0.099**
	2A	3A	0.00	0.07	-0.067	0.468
No. of Mirrors Deleted	1A	2A	1.43	0.06	1.366	**0.005**
	1A	3A	1.43	1.20	0.229	0.436
	2A	3A	0.06	1.20	-1.138	**0.031**
No. of Patterns Deleted	1A	2A	1.81	0.13	1.685	**0.000**
	1A	3A	1.81	0.73	1.076	**0.009**
	2A	3A	0.13	0.73	-0.608	0.149
Intuitive Organization	1A	2A	4.69	4.54	0.148	0.411
	1A	3A	4.69	5.00	-0.310	0.221
	2A	3A	4.54	5.00	-0.458	0.106
Intuitive Order	1A	2A	4.52	5.08	-0.559	**0.055**
	1A	3A	4.52	5.20	-0.676	**0.024**
	2A	3A	5.08	5.20	-0.117	0.459
Overall	1A	2A	4.63	4.94	-0.303	0.264
	1A	3A	4.63	5.40	-0.765	**0.013**
	2A	3A	4.94	5.40	-0.463	0.143

*$\alpha=0.100$

A graphical comparison of some of the key results of the second phase of the exercise is presented below.

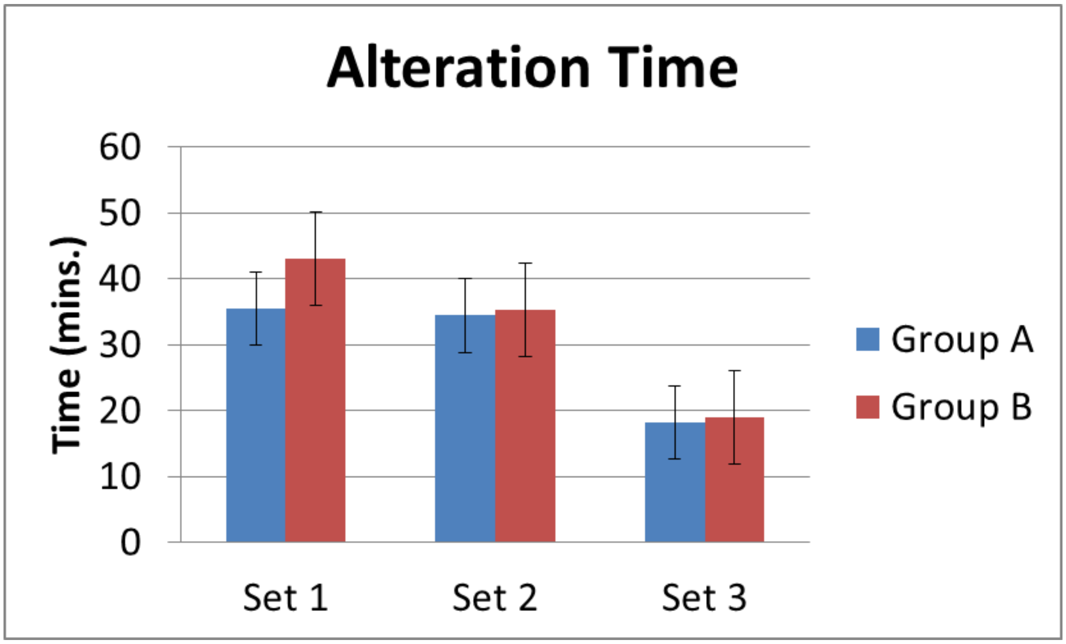

Figure 14 – Comparison of model alteration times in the second phase

Figure 14 shows a comparison of the alteration times during the second phase of the exercise. The trend for the model alteration times was similar to that of the model creation times – alteration times reduced with experience. Also, it should be noted that the models that were incentivized for the ease of alteration took less time for alteration as one would expect.

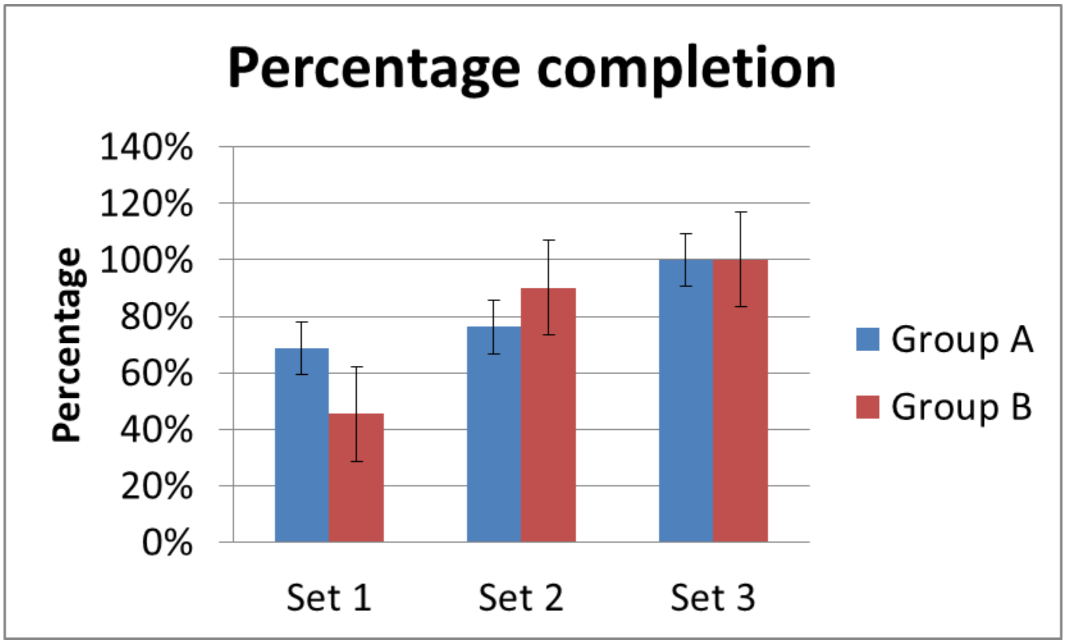

Figure 15 – Comparison of the percentages of participants completing the alteration exercise

In Figure 15, the percentages of participants in each of the groups completing the exercise are compared. The trend was similar to that seen in the first phase. One exception was that in Set 2 – fewer participants, who were working on models that were originally created for the ease of alteration, completed the alteration exercise. This could be attributed to the skill level differential of the participants. It should be remembered that the participants were randomly divided into Group 2A and Group 2B unlike in the case of Set 1 where they were divided based on a previous exercise.

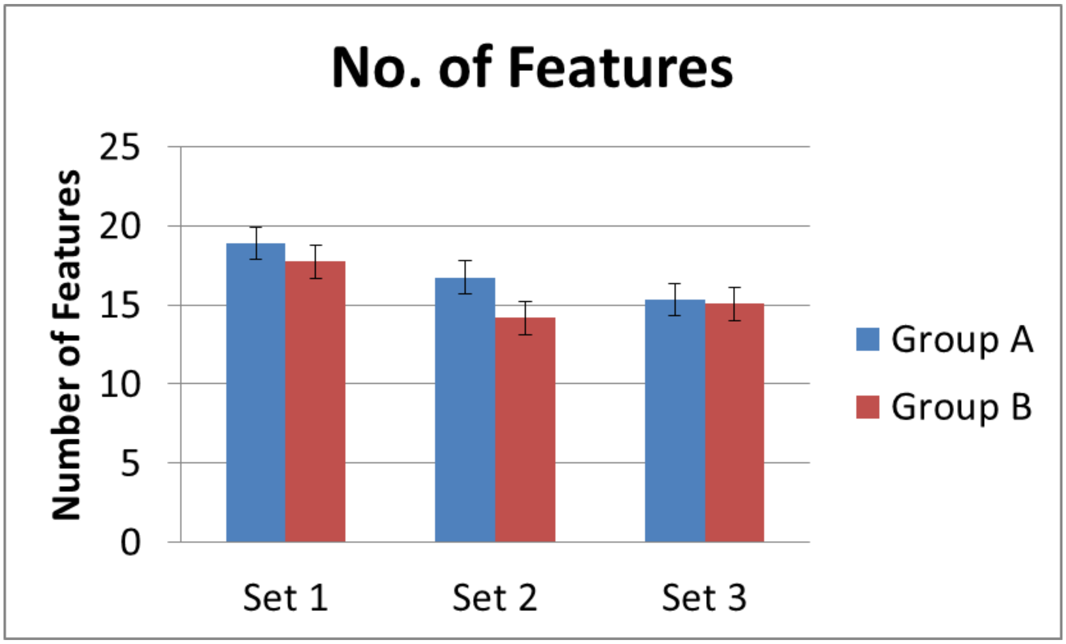

Figure 16 – Comparison of the number of features in the models from the second phase

The number of features in the altered models from the second phase are compared in Figure 16. The number of features in the altered models was the highest for Set 1 participants and the trend was similar to that seen in results of the first phase.

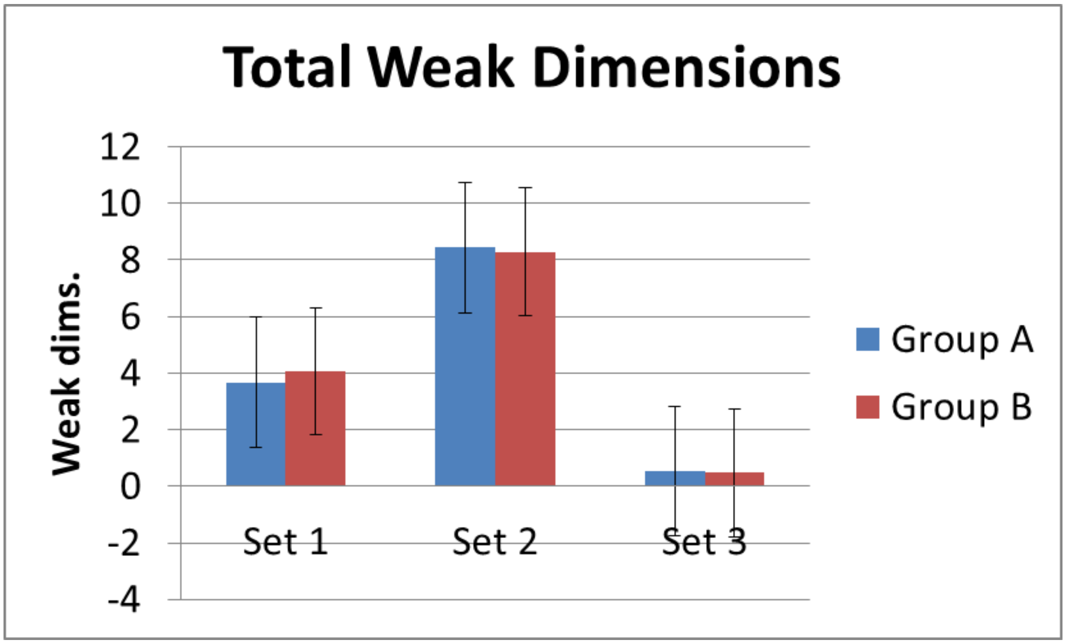

Figure 17 – Comparison of the total number of weak dimensions in the models from the second phase

A comparison of the number of weak dimensions in the models from the second phase of the exercise is presented in Figure 17. The trend for the number of weak dimensions was also the same as that seen in the first phase with the number of weak dimensions in the Set 2 models more than that of Set 1 and Set 3 models. The reason again could be attributed to the CAD package being used.

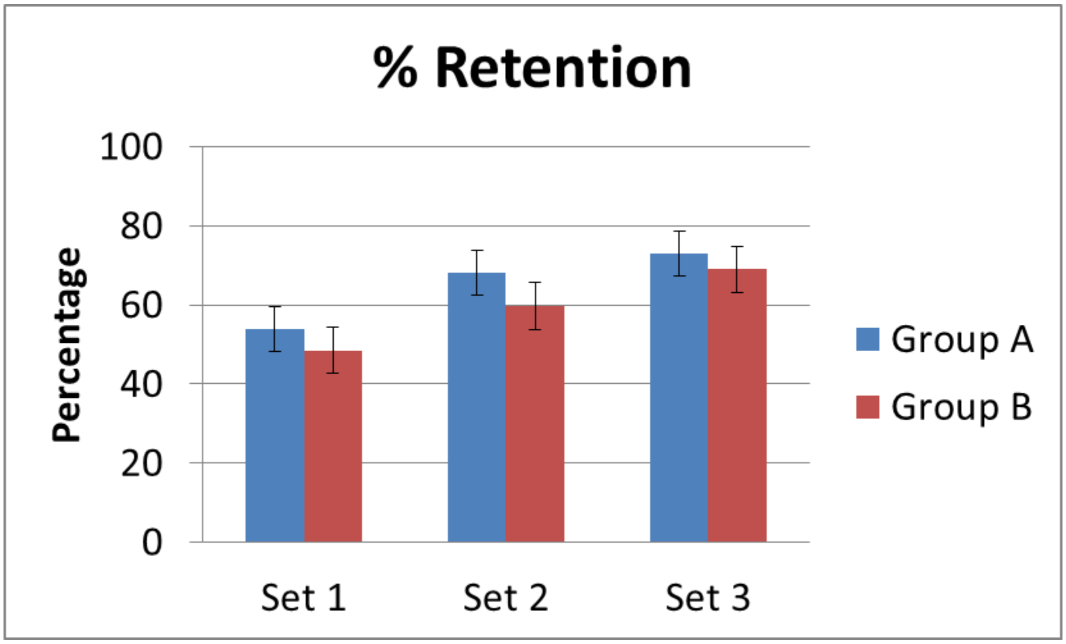

Figure 18 – Comparison of the percentage of features retained in the models from the second phase

The percentages of features retained during the alteration phase were compared and the results are shown in Figure 18. The number of features that were retained during alteration increased with experience and consistently more features were retained in those models that were originally created for the ease of alteration.

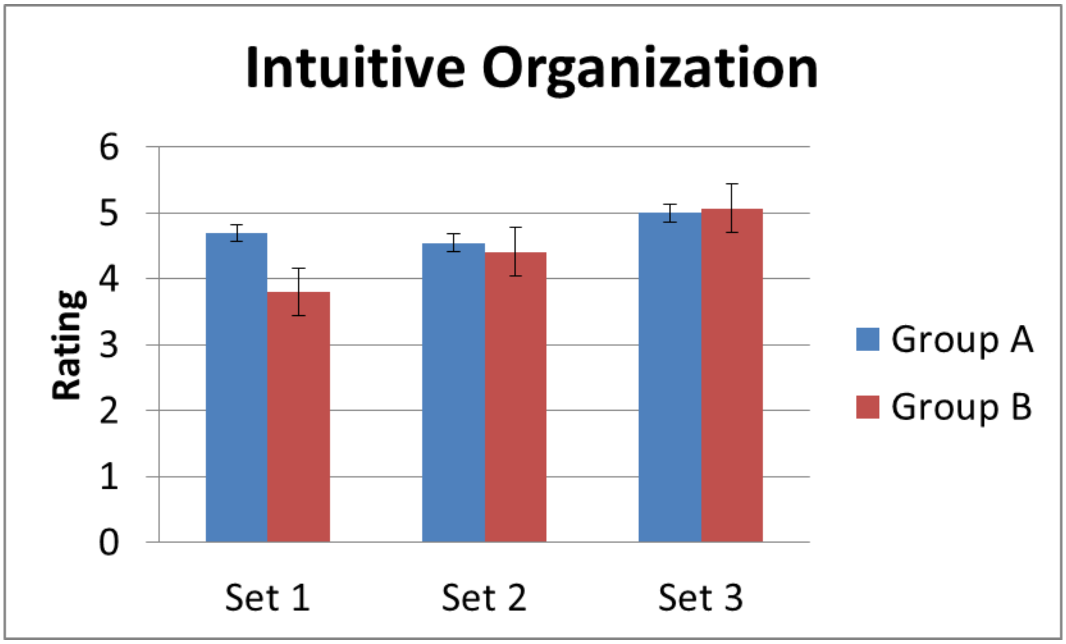

Figure 19 – Comparison of intuitive organization ratings

In Figure 19, the results of a comparison of the intuitive organization ratings given by the three sets of participants are presented. The intuitive organization ratings were the highest for Set 3 models. The models originally created for ease of alteration received better ratings in Set 1 and Set 2 models. However the models created for ease of alteration received a marginally lower rating in the case of Set 3 models.

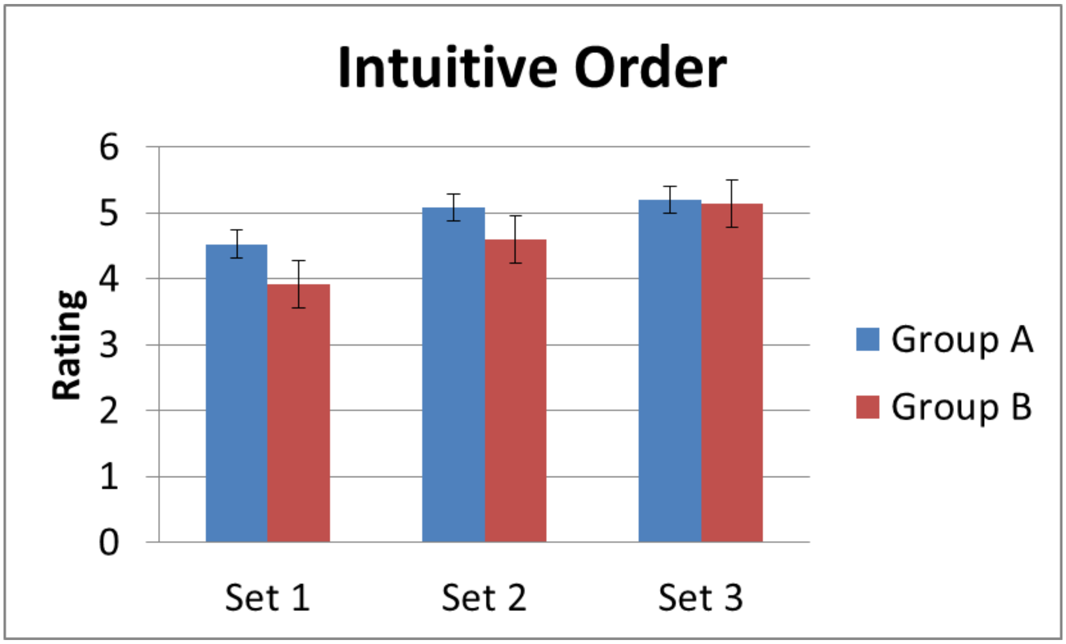

Figure 20 – Comparison of intuitive order ratings

A comparison of the results of the intuitive order ratings of the parent models following the alteration exercise is presented in Figure 20. In this case, the trend was clear – models created by more experienced participants were rated to have better ordered features; the ratings also indicated that the models created for ease of alteration had features that were better ordered.

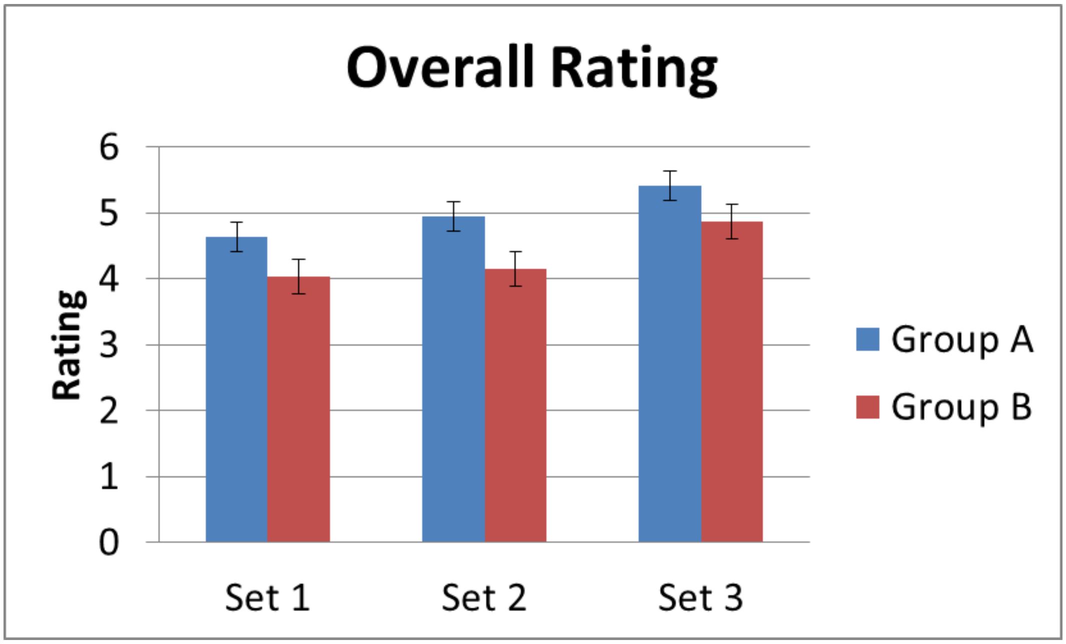

Figure 21 – Comparison of overall ratings

The overall ratings for the parent models given by the participants were compared and the results are presented in Figure 21. The trend for the overall rating was similar to that of the intuitive order rating – models created for ease of alteration received better ratings. Models created by more experienced participants received higher ratings and this could be attributed to the fact that fewer participants with less experience took the modeling exercise to completion. Those who failed to complete the exercise rated the parent models poorly.

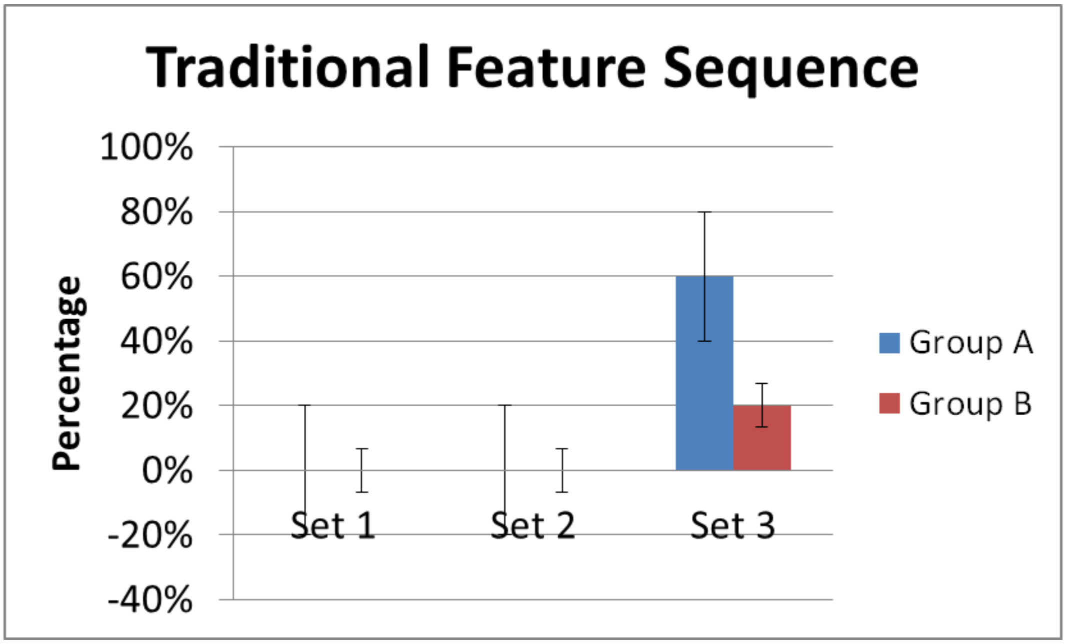

Figure 22 – Comparison of traditional feature sequence

Only models altered by Set 3 participants had the traditional feature sequence. This could be attributed to the industry experience that Set 3 engineers had gained. These results are presented in Figure 22.

Overall, the trends followed by the variables – modeling/alteration time, number of features, average number of segments, number of weak dimensions, number of mirrors and number of patterns were the same for both the incentivized groups in both the phases. Set 1 participants required the most amount of time while Set 3 required the least. This could be attributed to the skill level difference between the three sets of participants; the junior level students were the least skilled which in turn could be attributed to the time they were exposed to the CAD tool. It should be remembered that only part of the junior level CAD course was laboratory based while the senior level course was entirely laboratory based.

The Set 1 participants used the most number of features, followed by Set 2 participants and then by Set 3 participants who used the least number of features. This again could be attributed to the skill differential. With the lower skill level of the junior level students they were not able to create models with complex sketch geometry.

Interestingly, the models created by the senior level students had the maximum number of weak dimensions. This in part could be attributed to the CAD tool being used – Solidworks. Unlike Pro|Engineer, Solidworks does not automatically generate weak dimensions for the user to create completely constrained sketch geometry.

Set 1 participants used the highest number of mirrors and patterns followed by Set 3 participants while Set 2 participants used the least number of mirrors and patterns. It should be noted that Set 1 participants used several mirror features while Set 3 participants predominantly used mirrors in sketched geometry. Only the experienced engineers followed the correct feature order during model creation and alteration though, to varying degrees.

In phase two of the exercise as well, the trends for the number of features deleted, percentage retention, number of features changed, intuitive order, intuitive organization and overall ratings followed the same trends.

Set 1 participants deleted the highest number of features followed by Set 2 and Set 3 participants. As would be expected, the trend was the exact opposite in the case of percentage of features retained with Set 3 participants retaining the most number of features.

The design intent proxy ratings – intuitive order, intuitive organization and overall ratings all had the same trends: Set 3 models received the highest ratings, followed by Set

2 models leaving Set 1 models with the lowest ratings. This could be attributed to the percentage of participants taking the alteration exercise to completion. The participants who were not able to complete the alteration exercise rated the parent models low on the design intent proxy ratings.

7.6. Comparison with Parent Models

A graphical representation of the trends in how the altered model attributes compared with those of the parent models for the two incentive groups is presented in this section.

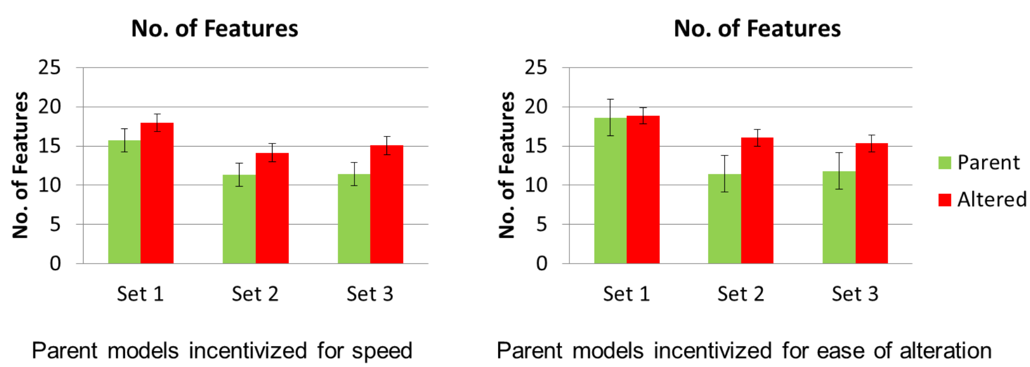

Figure 23 – Comparison of the number of features in the two incentive groups

As can be seen from Figure 23, the altered models in all three sets had more features than the parent models for both incentive groups. This indicated that participants made the necessary modifications to the models with the addition of simple features. This could also be driven by the altered design.

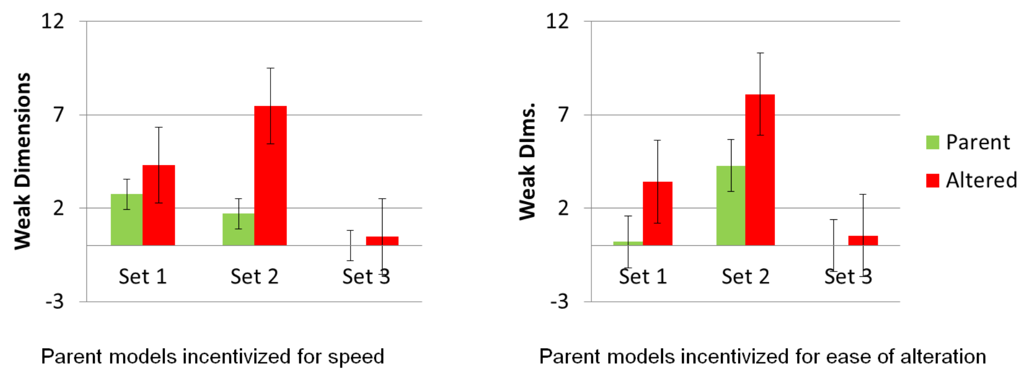

Figure 24 – Comparison of the number of weak dimensions in the two incentive groups

The results of a comparison of the number of weak dimensions between the two incentive groups are presented in Figure 24. There was a marked increase in the number of weak dimensions in the altered models. This was due to the removal of the incentive to consider the ease of further alteration of the model.

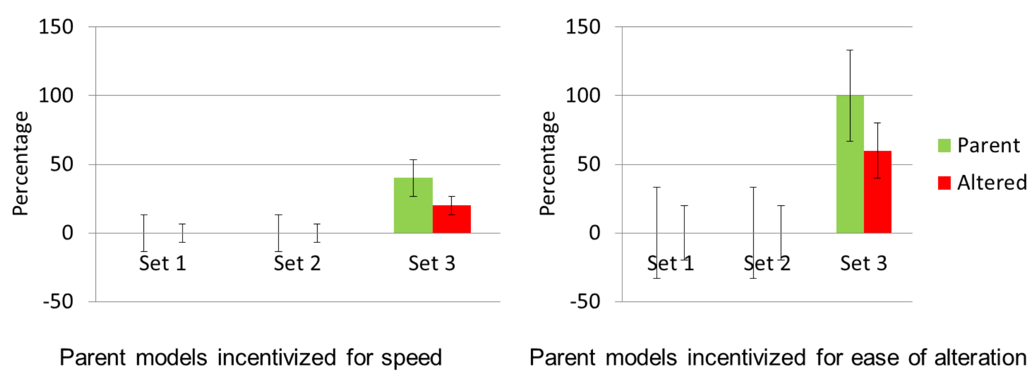

Figure 25 – Comparison of the number of models with the traditional feature sequence in the two incentive groups

A comparison of the number of models with the traditional feature sequence is presented in Figure 25. After alteration, the number of models with the traditional feature sequence reduced. However, parent models which had the traditional feature sequence influenced participants to insert features in the model tree to maintain the traditional feature sequence even after alteration.

7.7. Comparison of Survey Results

The results of the survey where the participants rated how the inclusion of a certain type of features and model attributes to the parent model would have affected the ease of alteration and perception of the model were compared. The results are summarized in Table 29 and Table 30.

Table 29 – Comparison of Survey Results

	F	Sig.*
Naming Features	1.908	0.153
Complex Features	1.880	0.157
Simpler Features	1.350	0.263
Patterns and Relations	0.131	0.878
Mirror and Copy	1.291	0.279
Referencing Datum Features	4.587	**0.012**

**α=0.100*

The analyses indicated that there was a statistically significant difference in referencing features from datum features. Set 3 participants strongly advocated this practice. From the ratings, it could be deduced that all participants wanted parent models to have features that were meaningfully named. It should be noted that only four of thirty-four participants from Group 1B and eight of fifteen participants from Group 2B had assigned meaningful names to features; no participant who was incentivized for speed and no experienced engineer renamed features. This showed the discrepancy in the expectation and the practices followed by engineers. The low rating on complex features and high rating on the use of simple features were clearly indicative of a preference for simple features. The ratings did not show a clear preference for the use of patterns, relations, copy or mirror features.

Table 30 – Tukey's HSD Test for Comparison of Survey Results

	Set (I)	**Set (J)**	**Mean (I)**	**Mean (J)**	**Mean Difference (I-J)**	**Sig. (1-tailed)***
Naming Features	1	2	5.85	5.51	0.340	0.194
	1	3	5.85	5.33	0.519	**0.083**
	2	3	5.51	5.33	0.179	0.415
Complex Features	1	2	2.82	3.37	-0.546	**0.083**
	1	3	2.82	2.83	-0.014	0.500
	2	3	3.37	2.83	0.533	0.149
Simpler Features	1	2	5.15	5.07	0.074	0.479
	1	3	5.15	5.57	-0.419	0.170
	2	3	5.07	5.57	-0.493	0.138
Patterns and Relations	1	2	4.66	4.49	0.168	0.439
	1	3	4.66	4.53	0.122	0.472
	2	3	4.49	4.53	-0.046	0.497
Mirror and Copy	1	2	4.07	4.54	-0.471	0.163
	1	3	4.07	4.50	-0.434	0.228
	2	3	4.54	4.50	0.037	0.498
Referencing Datum Features	1	2	5.18	4.85	0.327	0.254
	1	3	5.18	5.90	-0.720	**0.036**
	2	3	4.85	5.90	-1.046	**0.005**

*$\alpha=0.100$

7.8. Conclusions

This work explored the influence of incentives on 3D CAD model attributes during creation and the effect of CAD model attributes on the ease of alteration of the CAD model. Models created and altered by three sets of participants including students from a junior level CAD course, students from a senior level CAD course and experienced engineers from an Indian subsidiary of a renowned product development and services company. The attributes of the models and some derived parameters served as empirical evidence to derive some prescriptions for efficient CAD model creation and alteration.

Although incentives did not seem to directly affect the model attributes, the impact incentives had on CAD model alteration could be realized by comparing the parent and altered model attributes. The attributes of altered models from the second phase showed that engineers tend to compromise on proper modeling procedures when they work with CAD models created by others. Upon removing the incentive for the ease of further alteration, there was a significant increase in the number of weak dimensions, more features were incorrectly terminated and the traditional feature sequence was compromised. Parent models with the incentive for the ease of alteration also consistently received better design intent proxy ratings. Overall, during alteration of a CAD model, engineers tended to focus only on the necessary changes and failing to consider how the changes will impact overall order and organization of the model. If model alteration leads to a loss of design intent, after several iterations the model could reach a critical state where further modifications would lead to failure of some features and the model [52].

The students in the first two exercises were not as experienced and skilled with the CAD package they were learning. Their level of perception of the different possible ways of creating a CAD model, the effect of weak dimensions, ways to organize and order features were much lower compared to the professional CAD users. This could be validated through the consistently high number of weak dimensions and lack of models with the correct feature order in the models created and altered by students. The above reasons along with the fact that the models reflect the current trend in the industry, it becomes relevant to base the prescriptions for CAD model creation on the results obtained from the models created and altered by experienced engineers.

The prescriptions for CAD model creation and alteration based on the results of the exercises are listed below:

- **Build models using simple features**. It should be noted that the number of features increased sharply during alteration, especially in models which initially had a low feature count. In the results from the junior and senior exercises, number of features was significantly positively correlated with alteration time. Also in the exercise with the experienced engineers it was seen that fewer, more complex features adversely affected the perception of the model; models with complex sketches received poor order, organization and overall ratings. The consistently high ratings for the usage of simple features and the low ratings for the usage of complex features by all three sets of participants also support this prescription.
- **Completely constrain features.** It was seen that during alteration, the number of weak dimensions increased. Alteration time was statistically significantly positively correlated with weak dimensions indicating that engineers took longer to alter models with more weak dimensions (i.e., those that were not fully constrained). Models with weak dimensions were rated low on intuitive order, organization and overall ratings by experienced engineers. Manual dimensions take precedence over the weak dimensions. Any changes to the manually created dimensions automatically alter the weak dimensions and may result in undesirable changes to

the sketch, sometimes even leading to failure of the feature. Hence, it is preferred that features be fully constrained to better promote conveying design intent.

- **Maintain traditional feature sequence.** There was a significant positive correlation between the traditional feature sequence and intuitive order rating. The traditional feature sequence was also strongly positively correlated with the number of new features inserted between existing features of the model during alteration. In other words, engineers tried to maintain the order of the models by inserting new features between existing features rather than adding them as the last set of features in the altered model.
- **Alter existing features.** Almost all experienced engineers tried to modify existing features and not delete them to create new features. The average percentage retention (69% for Group 3B and 73% for Group 3A) was indicative of this fact. The number of features changed was significantly positively correlated with the design intent proxy ratings indicating that the models which were perceived well had features modified rather than deleted and replaced with new ones. This could reduce alteration time.

CHAPTER VIII

LIMITATIONS AND FUTURE WORK

One of the major limitations of this work is that only one CAD model of moderate complexity has been used to derive the conclusions. The results might be influenced by the design and the possible features that could be used to create a CAD model of the specified part. Also, the design for alteration might have influenced the way a particular model was altered. Hence the results are somewhat dependent on the designs provided to the engineers for creation and alteration. Another limitation of this work is the use of just two CAD platforms, Pro|Engineer and Solidworks. To be able to extend the results to CAD design in general, the data should be collected from other CAD platforms as well. A third limitation of this work is that there was only one alteration phase. Typically a CAD model may undergo several alterations before the final design is converged on. The current data collection method only involves collecting models created by participants and studying how the model attributes are affected by incentive. The thought process behind the participants' modeling activities was not captured.

Future work will be centered on mitigating some of the above listed limitations. To overcome the first limitation, multiple models with varying complexity will be used in the exercise. Also, multiple altered designs will be used better understand the impact of the altered design on the alteration process. To be able to generalize the results across CAD platforms, the exercise will be extended to expert users in different platforms including SolidWorks, NX and Inventor. There will be a third phase included to the exercise to understand the effect subsequent alterations have on attributes of the same CAD model. Another avenue for improvement would be the data collection method. A think-aloud modeling process could be employed to gather experts' thought process in creating and altering the CAD models. This would give more insight into the way experts tend to embed design intent into the models and how they associate CAD features and relations to their rationale.

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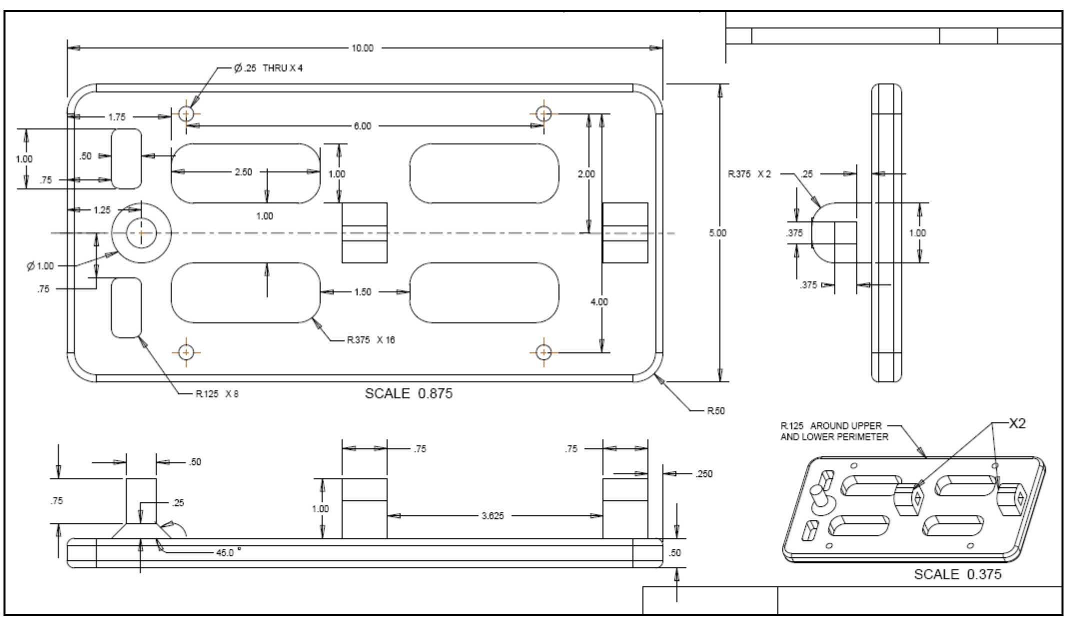
APPENDIX

Instructions for the First Phase of the Exercise

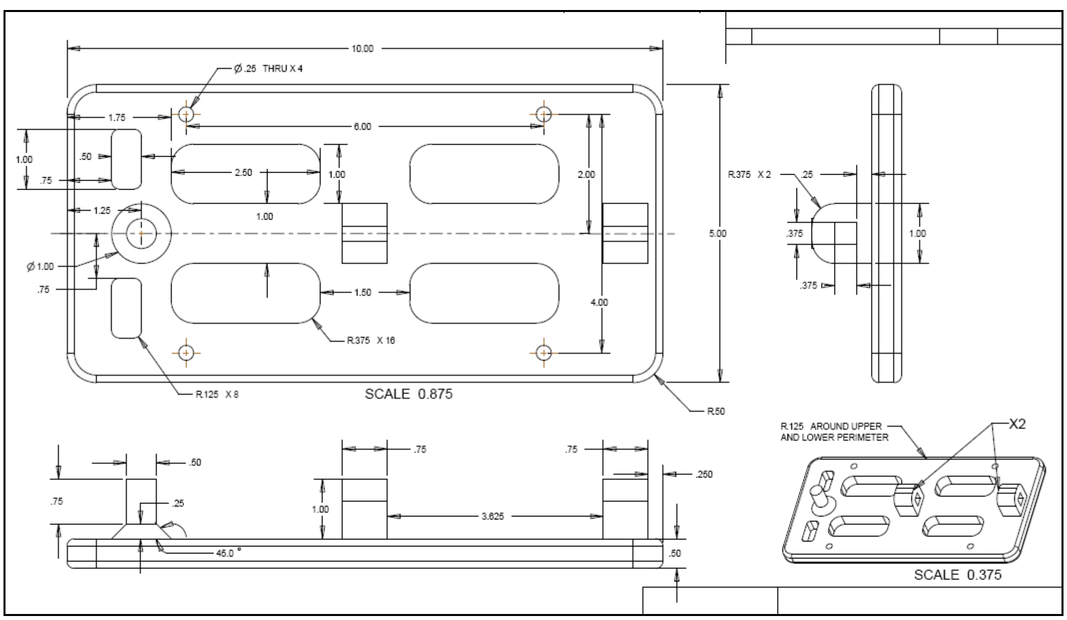
Incentive: Speed

1. Refer to the drawing below
2. Your goal is to create a model of the part in the drawing as **quickly** as you can. You will have a maximum of 60 minutes to create the model.
3. Start a timer before you start working. Note the time you take to create the model. It is preferred that you report the time to the nearest second.
4. Save your part with your name and the time you took to create the model. If your name is Ram, you are creating the model as **quickly** as you can and you took **7 mins and 0 seconds** your file name is **RAM_S_07_00**.
5. Send the part you created to – ramprasad.d@gmail.com
6. Include your experience (in years, example - 1.3 years) with ProE.



Incentive: Ease of Alteration

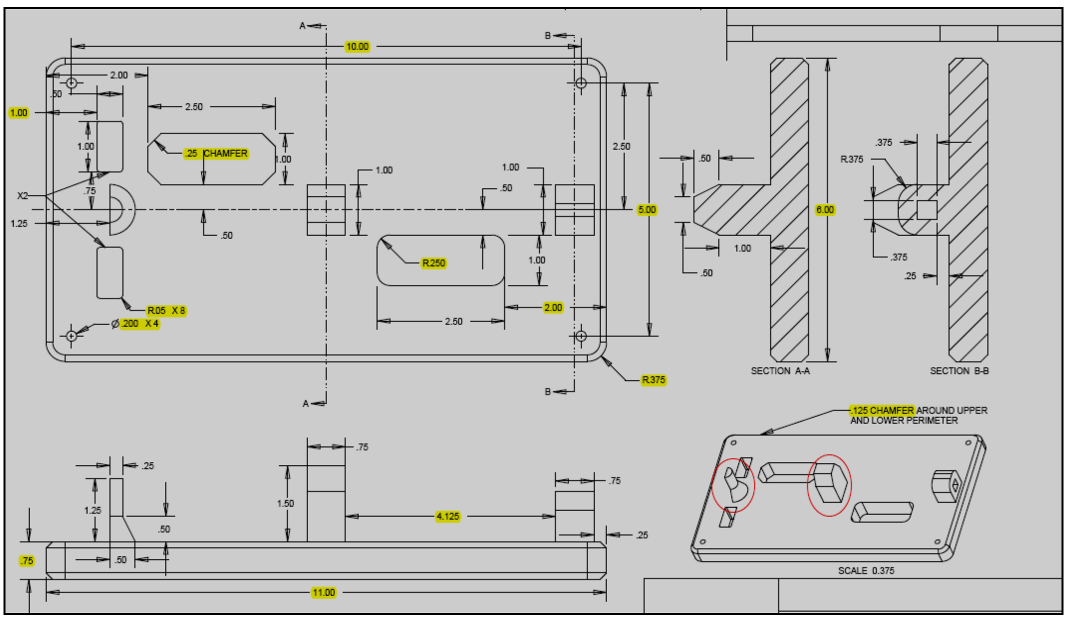
1. Refer to the drawing below.
2. Your goal is to create a model of the part in the drawing keeping in mind that it is **easy** for another engineer to understand and **make changes** to it. You will have a maximum of 60 minutes to create the model.
3. Start a timer before you start working. Note the time you take to create the model. It is preferred that you report the time to the nearest second.
4. Save your part with your name and the time you took to create the model. If your name is **Ram**, you are creating the model so that it is easy to **change** and you took **7 mins and 0 seconds** your file name is **RAM_C_07_00**.
5. Send the part you created as attachment to – ramprasad.d@gmail.com
6. Mention your experience (in years, example - 1.3 years) with ProE in the email



Instructions for the Second Phase of the Exercise

Model Alteration

1. Your objective is to make changes to the part that you are assigned based on the drawing in the next page **as quickly as possible**.
2. Rename your part as: **Filename_time**. For example, if the name of the part I got was “Harish_A" and I took 14 minutes and 45 seconds to complete the part, the part should be renamed to **Harish_A_14.45**.
3. Once you are done with this, you need to fill out a short questionnaire in the last page.
4. Please email your file and the filled questionnaire (this word doc) to ramprasad.d@gmail.com.
5. Thank you for your support!!



Survey

1. With respect to the design change exercise (completed today), how intuitive (easy to understand the organization) would you say the organization of model you worked with was?
   Not at all Intuitive – 1   2   3   4   5   6   7 – Very Intuitive

2. With respect to the design change exercise (completed today) how intuitive (easy to understand the order) would you say the order of the features in the model you worked with was?
   Not at all Intuitive – 1   2   3   4   5   6   7 – Very Intuitive

3. Overall, rate the model that you were given to change:
   I would dread – 1   2   3   4   5   6   7 – I would be very
receiving/working pleased to receive/work
with a model like this. with a model like this.

For the following questions, please rate the improvement (how helpful in your ability to understand and change the model) that the following changes to the model you had to modify would be.

4. Naming the features in the feature tree:
   Would Make – 1   2   3   4   5   6   7 – Would Be
Model Much Worse Very Helpful

5. Using more complex features (more geometry generated per feature):
   Would Make – 1   2   3   4   5   6   7 – Would Be
Model Much Worse Very Helpful

6. Using less complex features (less geometry generated per feature):
   Would Make – 1   2   3   4   5   6   7 – Would Be
Model Much Worse Very Helpful

7. Using more patterns and relations:
   Would Make – 1   2   3   4   5   6   7 – Would Be
Model Much Worse Very Helpful

8. Using more mirror, copy, and other similar feature generation methods:
   Would Make – 1   2   3   4   5   6   7 – Would Be
Model Much Worse Very Helpful

9. Referencing more features to datum planes/axes:
Would Make – 1 2 3 4 5 6 7 – Would Be
Model Much Worse Very Helpful

VITA

Ram Prasad Diwakaran was born in Chennai, India. He completed his schooling at Sri Aho Bila Math Higher Secondary School in 2001. He graduated from Birla Institute of Technology and Science with a Bachelor of Engineering (Hons.) degree in mechanical, in 2005. He worked for the Aerospace Product Development team at Honeywell Technology Solutions, Bangalore, India as a mechanical product development engineer until 2008. He graduated with his Master of Science degree in mechanical engineering in 2010 from Texas A&M University, College Station, Texas, USA.

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